THE THEORY OF THE GENE

BY

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Enlarged and Revised Edi

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THE SILLIMAN FOUNDATION

In the year 1883 a legacy of eighty thousand dollars was left to the President and Fellows of Yale College in the city of New Haven, to be held in trust, as a gift from her children, in memory of their beloved and honored mother, Mrs. Hepsa Ely Silliman.

On this foundation Yale College was requested and directed to establish an annual course of lectures designed to illustrate the presence and providence, the wisdom and goodness of God, as manifested in the natural and moral world. These were to be designated as the Mrs. Hepsa Ely Silliman Memorial Lectures. It was the belief of the testator that any orderly presentation of the facts of nature or history contributed to the end of this foundation more effectively than any attempt to emphasize the elements of doctrine or of creed; and he therefore provided that lectures on dogmatic or polemical theology should be excluded from the scope of this foundation, and that the subjects should be selected rather from the domains of natural science and history, giving special prominence to astronomy, chemistry, geology and anatomy.

It was further directed that each annual course should be made the basis of a volume to form part of a series constituting a memorial to Mrs. Silliman. The memorial fund came into the possession of the Corporation of Yale University in the year 1901; and the present work constitutes the nineteenth volume published on this foundation.

PREFACE

THE call for a revised edition of *The Theory of the Gene* has given me an opportunity to make several corrections of the original text as well as to bring into closer relation the references in the text to those in the bibliography. The bibliography has undergone a careful revision, a number of omissions have been made good, and a number of new references added.

In the same year in which the first edition of the *Theory of the Gene* appeared, I published a short article in the *Quarterly Review of Biology* in which certain questions relating to sex and fertilization were discussed. This topic was not taken up in the first edition, although intimately related to the subjects there considered. The sexual union of the plus and minus strains of certain fungi and algae, in relation to the fertilization of the eggs of the higher plants, raises a number of questions of fundamental interest to biologists. With the permission of the publishers, Williams, Wilkins, and Co., I have reprinted here those parts of the original article that bear on the question, as an extension of the chapter on "Other Methods of Sex-Determination involving Sex Chromosomes."

During the last two years many papers have appeared dealing with the number, and changes in number, of the chromosomes. It has not been possible to incorporate these new contributions, nor is it necessary, since, for the most

part, they have only expanded, rather than altered in any essential respect, the subjects discussed in the *Theory of the Gene*. In a few instances, however, I have added a brief account of the discoveries made since the earlier date, especially in those cases where the new results confirmed, expanded, or made less probable statements in the original text.

T. H. M.

Woods Hole, Mass.
August, 1928.

TABLE OF CONTENTS

List of Illustrations xiii

I. The Fundamental Principles of Genetics 1
- Mendel's Two Laws 1
- Linkage 10
- Crossing-Over 14
- The Simultaneous Interchange of Many Genes in Crossing-Over 20
- The Linear Order of the Genes 22
- The Theory of the Gene 25

II. Particulate Theories of Heredity 26

III. The Mechanism of Heredity 32
- The Mechanism of Mendel's Two Laws 33
- The Number of the Linkage Groups and the Number of the Chromosome Pairs 36
- The Integrity and Continuity of the Chromosomes 37
- Mechanism of Crossing-Over 39

IV. Chromosomes and Genes 45

V. The Origin of Mutant Characters 59

VI. Are Mutant Recessive Genes Produced by Losses of Genes? 72
- Recessive Characters and Absences of Genes 74
- The Bearing of Reverse Mutation (Atavism) on the Interpretation of the Mutation Process 85
- The Evidence from Multiple Allelomorphs 92
- Conclusions 94

VII. The Location of Genes in Related Species 95

VIII. The Tetraploids, or Fourfold Type 105
- Tetraploidy as a Means of Increasing the Number of Genes in a Species 130

IX. Triploids 131

X. Haploids 139

XI. Polyploid Series 150
- The Polyploid Wheats 150
- The Polyploid Roses 158
- Other Polyploid Series 165

XII. Heteroploids 172

XIII. Species Crossing and Changes in Chromosome Number 191

XIV. Sex and Genes 199
- The Insect Type (XX-XY) 199
- The Avian Type (WZ-ZZ) 206
- Sex-Chromosomes in Dioecious Flowering Plants 212
- Sex-Determination in Mosses 214

XV. Other Methods of Sex-Determination Involving the Sex-Chromosomes 219
- The Attachment of the X-Chromosome to Autosomes 219
- The Y-Chromosome 222
- Degeneration of Male-Producing Sperm 228
- The Elimination of one X-Chromosome from a Diploid Egg to Produce a Male 228
- Sex-Determination through the Accidental Loss of a Chromosome in Spermatogenesis 231
- Diploid Females and Haploid Males 233
- Sex in Haploids 239
- Sex and its Definition in Lower Plants 242

XVI. Intersexes 251
- Intersexes from Triploid Drosophila 251
- Intersexes in the Gypsy Moth 254
- The Free Martin 258

XVII. Sex Reversals 261
- Environmental Changes 262

Changes of Sex Associated with Age 265
Sex and Sex Reversal in Frogs 267
Transformation of Bidder's Organ of the Male Toad into an Ovary 277
Sex Reversal in Miastor 280
Sex Reversal in Birds 282
The Effect of Ovariotomy in Birds 283
The Sex of Parabiotic Salamander Twins 286
Sex Reversal in Hemp 287

XVIII. Stability of the Gene 292

XIX. General Conclusions 311
The Effects Produced by a Change in Chromosome Number and by a Change in a Gene 311
Is the Mutation Process Due to a Degradation of the Gene? 318
Are Genes of the Order of Organic Molecules? 320

Bibliography 322

Index 352

LIST OF ILLUSTRATIONS

FIG.		PAGE
1.	Inheritance of tall *versus* short peas	2
2.	Hybrid pea back-crossed to recessive parent	3
3.	Inheritance of brown *versus* blue eyes	4
4.	Back-cross of hybrid to recessive blue-eyed individual	5
5.	Inheritance of flower color of four-o'clock (Mirabilis)	6
6.	Distribution of genes in cross shown in figure 5	7
7.	Inheritance of yellow round and green wrinkled peas	8
8.	Distribution of genes for three pairs of characters	9
9.	Inheritance of two linked characters in sweet peas	11
10.	Inheritance of four linked characters in Drosophila	13
11.	Inheritance of two sex-linked characters in Drosophila	15
12.	Inheritance of the same characters as in figure 11 in reciprocal combination	16
13.	Inheritance of white eyes and miniature wings of Drosophila (back-cross)	18
14.	Inheritance of white eyes and forked bristles of Drosophila	19
15.	The location of nine sex-linked recessive genes	21
16.	Crossing-over between garnet and vermilion in the series of genes shown in figure 15	21
17.	Crossing-over between echinus and cross-veinless in the series of genes shown in figure 15	21
18.	Double crossing-over	21
19.	Chart of the linked genes of Drosophila	23
20.	The order of the genes, yellow, white, bifid, of Drosophila	24
21.	Maturation of sperm-cell	33
22.	Maturation of the egg	34
23.	Independent assortment of X and a pair of autosomes	35
24.	Haploid chromosome groups of edible pea, sweet pea, and Indian corn	37
25.	Nuclei of daughter cells of Ascaris	39
26.	Conjugation of chromosomes of Batrachoseps	41
27.	Twisted chromosomes of Batrachoseps	42
28.	Conjugation of chromosomes of a planarian, Dendrocoelum	43
29.	Normal and haplo-IV female of Drosophila	47

FIG. PAGE
30. Three mutant types of chromosome-IV group of Drosophila 48
31. Cross between haplo-IV and diploid eyeless fly 49
32. Haplo-IV and triplo-IV female of Drosophila 50
33. Cross between triplo-IV and diploid eyeless Drosophila (upper half of diagram). Continuation of last (lower half of diagram), mating of heterozygous triplo-IV to diploid eyeless 51
34. Primary non-disjunction. XX-egg fertilized by Y-sperm . . 53
35. Non-disjunction. White-eyed XXY female fertilized by red-eyed XY male 54
36. Superfemale of Drosophila. (2n + 3X) 56
37. Fertilization of egg with attached X (double yellow female) by sperm of wild-type male 57
38. Sex-linked inheritance of the mutant type, white eyes of Drosophila 60
39. Sex-linked inheritance of a light-colored mutant type lacticolor of Abraxas 61
40. Head of mutant type of Drosophila, Lobe² (eye) 62
41. Mutant type of Drosophila, Curly wings 63
42. Oenothera Lamarckiana and O. gigas 69
43. Combs of domestic races of fowls 73
44. Mutant type—Notch wings—of Drosophila 78
45. Inheritance of Notch wings 79
46. Notch-deficiency; duplication of not-vermilion; duplication of not-yellow 80
47. Fertilization of egg-cell of flowering plant, and development of endosperm 83
48. Triploid condition of (a) two floury genes *versus* one flinty gene; (a′) two flinty *versus* one floury gene 84
49. Types of bar-eye of Drosophila 87
50. Diagram of bar female heterozygous for forked and fused, by forked bar fused male 88
51. Diagram of crossing-over of bar; of infra-bar; of bar-infra-bar 90
52. Diagram of crossing-over of bar-infra-bar heterozygous for forked and fused; of infra-bar-bar heterozygous for forked and fused 91
53. Cross between two species of tobacco 96
54. Cross between two species of snapdragon 97

FIG. PAGE
55. Cross between a mutant type of one species of snapdragon and a normal type of another species 97
56. Different recombination types resulting from cross of two species of snapdragon (figure 55) 98
57. Varieties of two species of Helix, and hybrid between them . 99
58. Drosophila melanogaster and D. simulans 100
59. Homologous genes of Drosophila melanogaster and D. simulans. 101
60. Chart of chromosomes of Drosophila virilis 102
61. Chart of chromosomes of Drosophila obscura 103
62. Chromosomes of Metapodius with three m-chromosomes and their reduction 106
63. First two divisions of egg of Ascaris 108
64. Polar, metaphase group of chromosomes of diploid and tetraploid Artemia 109
65. Diploid and tetraploid chromosome group of Oenothera . . 110
66. Maturation of pollen mother cells of Oenothera 111
67. Grafting of tomato and nightshade, and a resulting chimaera 113
68. Diploid and tetraploid nightshade 114
69. Seedlings, flowers, and cells of diploid and tetraploid nightshade 115
70. Haploid and diploid cells of normal nightshade; diploid and tetraploid cells of tetraploid 116
71. Same of tomato 117
72. Normal and tetraploid Datura 118
73. Haploid, diploid, triploid, and tetraploid Datura 119
74. Diploid and tetraploid chromosome groups (second maturation division) of Datura 120
75. Methods of conjugation of chromosomes of diploid, triploid, and tetraploid Datura 121
76. Conjugation of chromosomes of tetraploid Datura . . . 122
77. Chromosome groups of Euchlaena, annual and perennial, of Indian corn, and of hybrid 123
78. Diagram of gametophyte and sporophyte generation of dioecious moss 125
79. Diagram of formation of 2n gametophyte from regeneration of 2n sporophyte, and 4n gametophyte by regeneration from 4n sporophyte 127
80. Triploid chromosome-group of hyacinth 132
81. Maturation division of diploid and triploid Datura . . . 133

FIG. PAGE
82. Diploid and triploid Drosophila 135
83. Constriction of egg of Triton isolating one half with a single sperm 140
84. Haploid plant of Datura 143
85. Diagram of two maturation divisions of egg of bee, and fertilization of egg by sperm 144
86. Two maturation stages of the germ-cell of the honey bee . 146
87. Parthenogenetic female, sexual female, and male, of Hydatina 147
88. Chromosomes of diploid, tetraploid, and hexaploid wheats . 151
89. Normal maturation divisions of Einkorn, Emmer, and Vulgare wheats 153
90. Maturation divisions of hybrid between Emmer and Vulgare wheats 154
91. Same as last, illustrating a somewhat different account of process 155
92. Multiple chromosome groups of roses 159
93. Maturation division of pollen cells of a hybrid rose 161
94. Maturation division of egg-cell of a hybrid rose 162
95. Five types of hybrid canina roses 164
96. Maturation of pollen of Hieracium 166
97. Chromosomes of chrysanthemums 167
98. Nuclear sizes of varieties of chrysanthemums 168
99. Chromosomes of chrysanthemums 168
100. Oenothera lata, heterosomic type 173
101. Mutant types of seed capsules of Datura 178
102. Normal and heterosomic (2n + 1 and 2n + 2) types of seed capsules of Datura 179
103. Tetraploid and heterosomic tetraploid types of Datura . . 183
104. Union of chromosomes in Primary and Secondary types of Datura 184
105. Diagram of hypothetical reversal of conjugating chromosomes 185
106. Conjugation of chromosomes of Primary and Secondary heterosomic types of Datura 186
107. Imaginary relation of mutant types to specific chromosomes in Oenothera 188
108. Diploid and haploid chromosome groups of Drosera . . . 191
109. Chromosome groups of Crepis setosa and C. biennis and that of hybrid 195

FIG. PAGE
110. Chromosome groups of perennial and annual teosinte . . 196
111. Chromosome groups of two species of poppies and that of hybrid 197
112. Male and female chromosome groups of Protenor . . . 200
113. Male and female chromosome groups of Lygaeus 200
114. Diagram of XX-XY type of sex determination 201
115. Sex-linked inheritance of white eyes of Drosophila . . . 202
116. Chromosome groups in man 203
117. Separation of X- and Y-chromosomes in spermatogenesis in man 204
118. Diagram of WZ-ZZ type of sex-determination 205
119. Male and female chromosome groups in fowl 206
120. Sex-linked inheritance in poultry 207
121. Sex-linked inheritance in a moth, Abraxas 208
122. Chromosomes of egg of moth, Fumea 209
123. Sex-determination in dioecious plants 213
124. Female and male prothallia of liverwort, with respective haploid chromosome groups 215
125. Method of combining male- and female-determining groups of mosses 217
126. Separation of X-chromosome from autosomes in Ascaris . 219
127. Diagram of sex determination when the X-chromosomes are united to autosomes 220
128. Diagram of paternal inheritance in a fish, Lebistes, with crossing-over between X and Y 223
129. Diagram of inheritance of white *versus* red body-color of fish 224
130. Diagram of second generation from last 225
131. Diagram of inheritance of white and red body-color of fish with crossing-over between X and Y 226
132. Diagram of theoretical crossing-over between autosomes to which the X-chromosomes are attached 227
133. Two maturation divisions of bearberry aphid 229
134. Polar spindle of male-producing egg, and polar spindle of female-producing egg of Phylloxera 230
135. Two maturation divisions of sperm-cells of Rhabditis . . 231
136. Two maturation divisions (polar body formation) of egg of Rhabditis 232
137. Parthenogenetic female, male-egg-producing female, sexual egg-producing female, and male of Brachionus 234

FIG. PAGE
137a. Swarming gametes of Ectocarpus 246
138. Sex formulae of diploid, triploid, tetraploid types of Drosophila 252
139. Superfemale and supermale of Drosophila 253
140. Normal male and female and two mosaics of gypsy moth . . 255
141. Union of chorions of two foetal calves, one of which becomes a free martin 258
142. Normal male, normal female, and parasitized male of Inarchus 262
143. Larva of Perla and ovotestis of same 267
144. Chromosome groups of spermatogonia and oögonia, and diploid male egg of Perla 268
145. Chromosome groups of frog 272
146. Hermaphroditic condition in frog 275
147. Bidder's organs of toad 277
148. Transformation of Bidder's organs, after castration, into ovaries 278
149. Female and male hemp plants 288
150. Four pure lines and general population of Princess bean . . 295
151. Types of hooded rat 297
152. Normal and mutant types of abnormal abdomen of Drosophila 302
153. Distribution of pigment cells in different color types of pupae of cabbage butterfly 304
154. Diagram of percentages of color types of pupae of cabbage butterfly after exposure to different colored lights 306
155. Guinea pigs with alcoholic ancestry 307
156. Young rat with hemorrhagic areas after exposure of mother to radium 309

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CHAPTER I

THE FUNDAMENTAL PRINCIPLES OF GENETICS

THE modern theory of heredity is derived from numerical data obtained by crossing two individuals that differ in one or more characters. The theory is primarily concerned with the distribution of units between successive generations of individuals. In the same sense in which the chemist postulates invisible atoms and the physicist electrons, the student of heredity appeals to invisible elements called genes. The essential point in this comparison is that both the chemist and the student of heredity—the geneticist—have reached their conclusion from numerical and quantitative data. The theories justify themselves in so far as they permit numerical and quantitative prediction of a specific kind. In this essential respect the theory of the gene differs from earlier biological theories that have also postulated invisible units to which were arbitrarily assigned any desired properties. The theory of the gene reverses this order and derives the properties of the genes, so far as it assigns properties to them, from the numerical data alone.

Mendel's Two Laws.

We owe to Gregor Mendel the discovery of two of the fundamental laws of heredity on which the modern theory of heredity is based. Later work, done by others during the present century, has carried us further in the same direction and made possible the elaboration of the theory on a much broader basis. Mendel's discovery may be illustrated by a few familiar examples.

He crossed a tall variety of edible pea to a short variety. The offspring, or hybrids, F_1, were all tall (Fig. 1). These were allowed to self-fertilize. Their offspring were

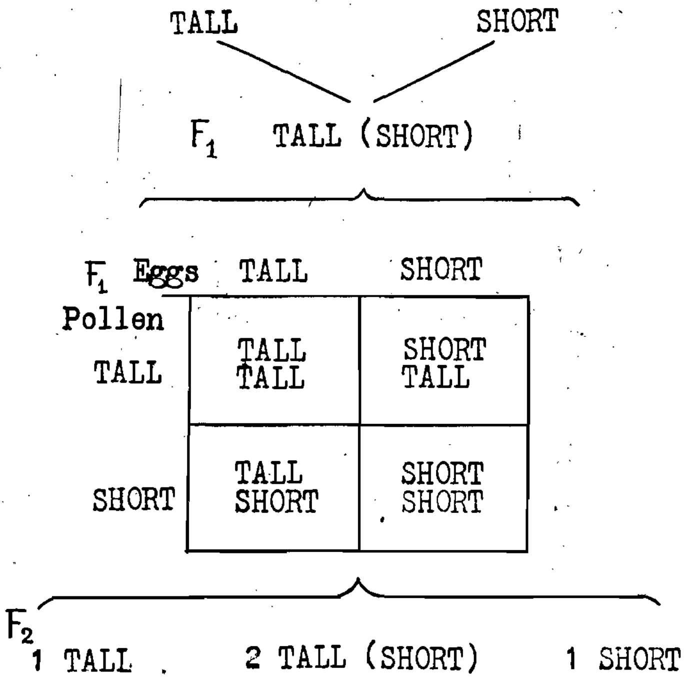


FIG. 1.

Tall peas crossed to short peas giving in the first generation (F_1), tall peas that are "hybrid," *viz.*, tall (short). The recombination of the gametes (eggs and pollen grains) are shown in the square. Three tall to one short peas result in the next or second (F_2) generation.

tall and short in the ratio of three talls to one short. If the tall variety contains in its germ-cells something that makes the plants tall; and if the short variety carries something in its germ-cells that makes the plants short, the hybrid contains both; and since the hybrid is tall it is

evident that when both are brought together the tall dominates the short, or, conversely, short is recessive to tall.

Mendel pointed out that the 3 to 1 ratio that appears in the second generation can be explained by means of a very simple hypothesis. If the element for tall and the one for short (that are both present in the hybrid) separate in the hybrid when the eggs and pollen

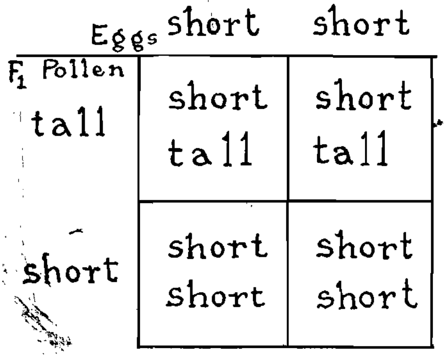


FIG. 2.

A "back-cross" of F_1 hybrid, tall (short) peas to the recessive type (short), giving equal numbers of tall and short offspring.

grains come to maturity, half the eggs will contain the tall and half the short element (Fig. 1). Similarly for the pollen grains. Chance fertilization of any egg by any pollen grain will give on the average three talls to one short; for, when tall meets tall a tall plant is produced; when tall meets short a tall plant results; when short meets tall, a tall plant is produced; and when short meets short, a short plant arises.

Mendel put this hypothesis to a simple test. The hybrid was back-crossed to the recessive type. If the germ-cells of the hybrid are of two kinds, tall and short, there should

be two kinds of offspring, tall and short in equal numbers (Fig. 2). The results confirm the expectation.

The same relation shown by the tall and the short peas can be illustrated by the inheritance of eye color in man. Blue eyes mated to blue, give only blues; brown eyes

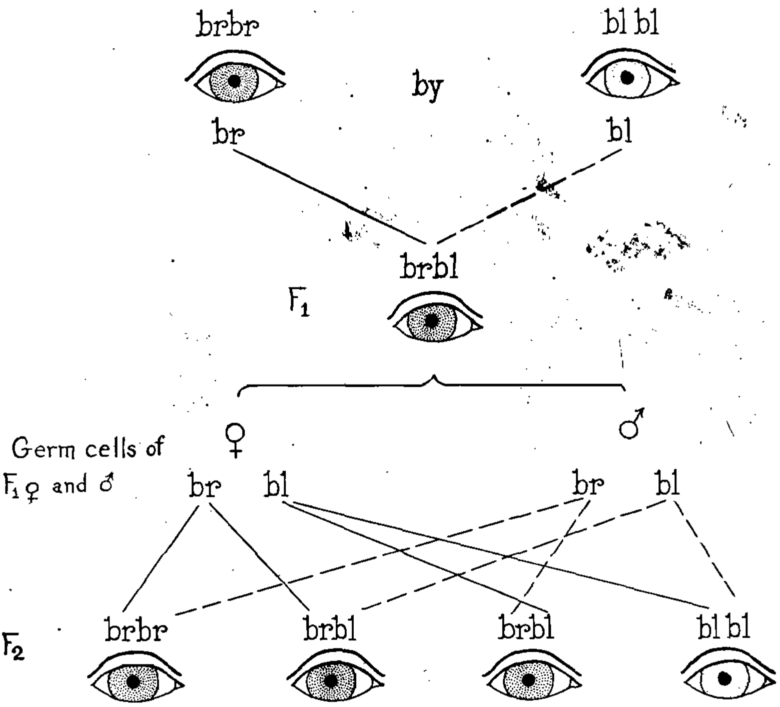


Fig. 3.
Inheritance of brown eyes (brbr) *versus* blue (blbl) eyes in man.

bred to brown give only brown, provided the browns have had only a brown ancestry. If a blue mates with a pure brown, the children are brown (Fig. 3). If two individuals that have arisen from such parentage marry, their children will be brown- and blue-eyed in the ratio of 3 to 1.

If a hybrid brown-eyed individual (F_1 brown-blue) marries a blue-eyed individual, half the children will have brown, and half will have blue eyes (Fig. 4).

There are other crosses that give, perhaps, a more striking illustration of Mendel's first law. For instance, when a red and a white-flowered four-o'clock are crossed, the hybrid has pink flowers (Fig. 5). If these pink-

Sperm \ Eggs	blue	blue
brown	blue brown	blue brown
blue	blue blue	blue blue

FIG. 4.

A "back-cross" of a brown-eyed, F_1, individual, heterozygous for blue eyes, to the recessive type, blue eyes, giving equal numbers brown-eyed and blue-eyed offspring.

flowered hybrid plants self-fertilize, some of their offspring (F_2) are red like one grandparent, some of them pink like the hybrid, and others white like the other grandparent, in the ratio of 1:2:1. Here one original parental color is restored when red germ-cell meets red, the other color is restored when white meets white, and the hybrid combinations appear as often as red meets white, or white meets red. All the colored flowered plants in the second generation taken together are to the white-flowered plants as 3:1.

In passing it is important to note two facts. The red and the white F_2 individuals are expected to breed true, because they contain the elements for red, or for white,

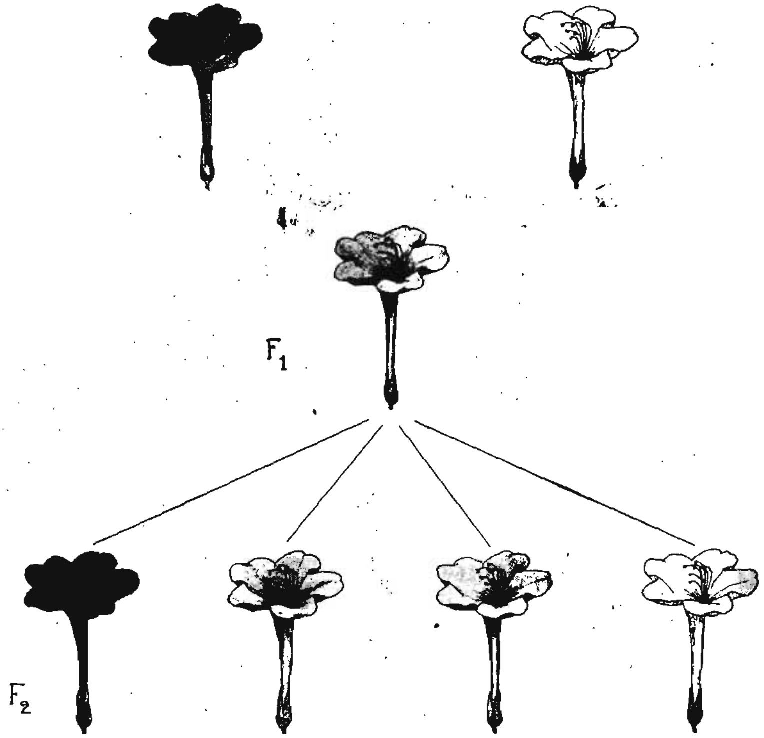


FIG. 5.

A cross between a red-flowered four-o'clock (Mirabilis Jalapa) and a white-flowered four-o'clock, giving pink in F_1, and one red, two pink, one white in F_2.

twice present (Fig. 6), but the pink F_2 individuals should not breed true, since they are like the first hybrid generation, and contain one red and one white element (Fig. 6). All this turns out to be true when these plants are tested.

constitute a pair of contrasted characters giving a 3 to 1 ratio in the second generation, and that round and wrinkled constitute another pair.

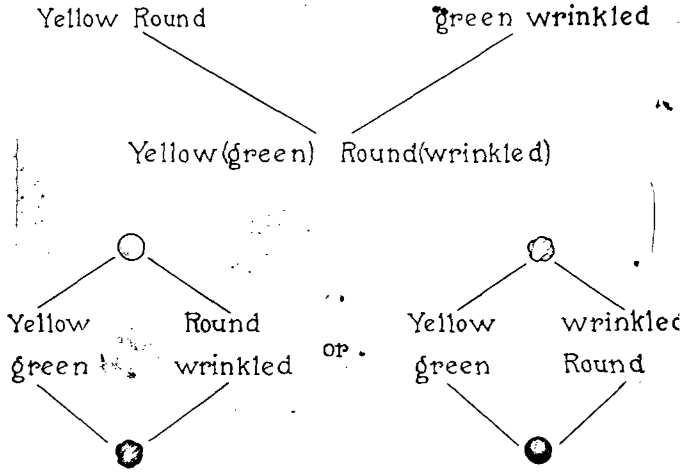


FIG. 7.

Diagram to illustrate the inheritance of two pairs of Mendelian characters, *viz.*, yellow-round and green-wrinkled peas. In the lower part of the diagram the four classes of F_2 peas are shown, *viz.*, the two original classes, yellow-round and green-wrinkled, and the two recombination classes, yellow-wrinkled and green-round.

The offspring were yellow and round (Fig. 7). When selfed, they produced four kinds of individuals, yellow round, yellow wrinkled, green round, and green wrinkled in the ratio of 9 : 3 : 3 : 1.

Mendel pointed out that the numerical results found here can be explained, if the separation of the elements for yellow and for green is independent of that for round and wrinkled. This would give four kinds of germ-cells

in the hybrid, yellow round, yellow wrinkled, green round, and green wrinkled (Fig. 8).

If the fertilization of the four kinds of ovules by the four kinds of pollen grains is at random, there will be

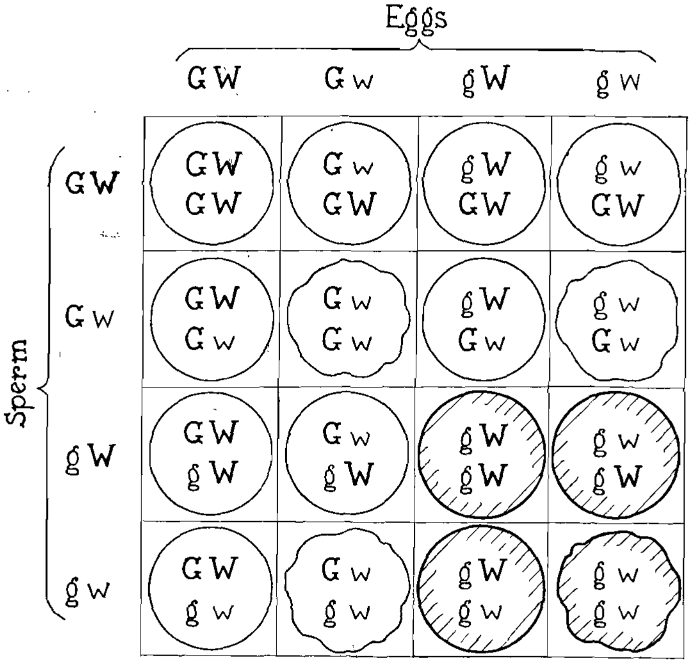


FIG. 8.

Diagram illustrating the sixteen F_2 recombinations (from yellow-round and green-wrinkled peas) that result when the four kinds of eggs and the four kinds of pollen grains of the F_1 hybrid come together.

sixteen combinations possible. Remembering that yellow dominates green, and that round dominates wrinkled, these sixteen combinations will fall into four classes, that are in the ratios of 9:3:3:1.

The results of this experiment show that it can no longer be assumed that the whole parental germ-materials

are separated in the hybrid; for yellow and round that went in together have, in some cases, come out separated. Similarly for green and wrinkled.

Mendel also showed that when three, and even four, pairs of characters enter a cross their elements are independently assorted in the germ-cells of the hybrid.

It might, then, have seemed justifiable to extend this conclusion to as many pairs of characters as enter any particular cross. This would mean that there are as many independent pairs of elements in the germinal material as there are possible characters. Subsequent work has shown, however, that Mendel's second law of independent assortment has a more restricted application, since many pairs of elements do not assort freely, but certain elements that enter together show a tendency to remain together in succeeding generations. This is called linkage.

Linkage.

Mendel's paper was recovered in 1900. Four years later Bateson and Punnett reported observations that did not give the numerical results expected for two independent pairs of characters. For instance, when a sweet pea having purple flower-color and long pollen grains is crossed to one with red flowers and round pollen grains, the two types that go in together come out together more frequently than expected for independent assortment of purple-red and round-long (Fig. 9). They spoke of these results as due to repulsion between the combinations purple and long and red and round, that came from opposite parents. Today these relations are called linkage. By linkage we mean that when certain characters enter a cross together, they tend to remain together in later generations, or, stated in a negative way, certain pairs of characters do not assort at random.

It would seem, then, so far as linkage holds, that there

e limits to the subdivision of the germinal material. or example in the vinegar fly, Drosophila melanogaster, ere are known about 400 new mutant types that fall to only four linkage groups.

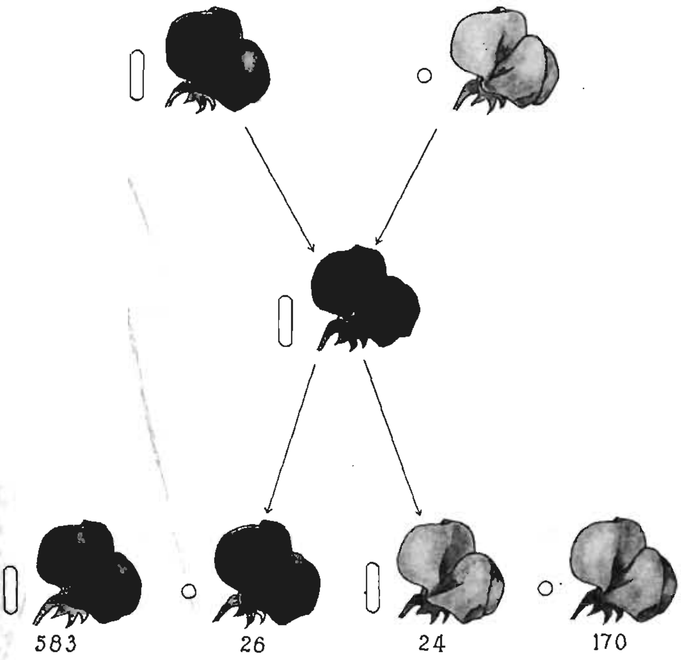


FIG. 9.

Cross between a sweet pea with purple flowers and long pollen grains and one with white flowers and round pollen grains. In the lower line the four classes of F_2 individuals appeared in the proportions given.

One of these groups of characters of Drosophila is said be sex-linked, because in inheritance the characters ow certain relations to sex. There are about 150 of these x-linked mutant characters. Several of them are modifications of the color of the eye, others relate to its shape

or its size, or to the regularity of the distribution of its facets. Other characters involve the body color; others the shape of the wings, or the distribution of its veins; others the spines and hairs that cover the body.

A second group of about 120 linked characters includes changes in all parts of the body. None of the effects are identical with those of the first group.

A third group of about 130 characters also involves all parts of the body. None of these characters are the same as those of the other two groups.

There is a small fourth group of only three characters: one involves the size of the eyes, leading in extreme cases to their total absence; one involves the mode of carriage of the wings; and the third relates to the reduction in size of the hairs.

The method of inheritance of linked characters is given in the following example. A male Drosophila with four linked characters (belonging to the second group), black body color, purple eyes, vestigial wings, and a speck at the base of the wings (Fig. 10), is crossed to a wild type female with the corresponding normal characters, that may be called gray body color, red eyes, long wings, and absence of speck. The offspring are wild type. If one of the sons[1] is now crossed to a stock female having the four recessive characters (black, purple, vestigial, speck), the offspring are of two kinds only, half are like one grandparent with the four recessive characters, and the other half are wild type like the other grandparent.

Two sets of contrasted (or allelomorphic) linked genes went into this cross. When the germ-cells in the male hybrid matured, one of these sets of linked genes went into half of the sperm-cells and the corresponding allelomorphic set into the wild type half of the sperm-

[1] It is necessary to make this reservation as to the *male* Drosophila, because in the female these same characters are not *completely* linked.

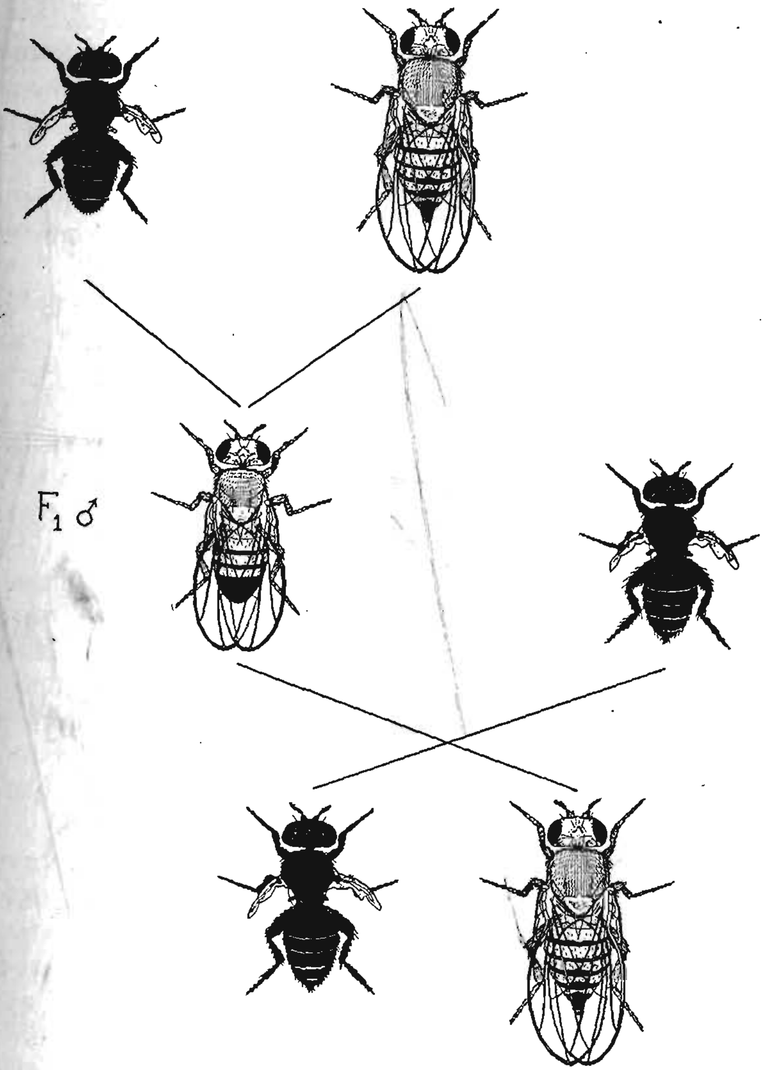


FIG. 10.

The inheritance of four linked, recessive characters, *viz.*, black body color, purple eyes, vestigial wings, and speck, *versus* their normal allelomorphs of the wild type fly. The F_1 male is "back-crossed" to a female of the multiple recessive stock, giving in the second generation (shown below) only the two grand parental combinations.

cells. This was revealed, as described above, by crossing the hybrid (F_1) male to a female pure for the four recessive genes. All of her mature eggs contain one set of four recessive genes. Any egg fertilized by a sperm with one set of the dominant wild type genes should give a wild type fly. Any egg fertilized by a sperm with the four recessive genes (which are the same as those in the female here used) should give a black, purple, vestigial, speck fly. These are two kinds of individuals obtained.

Crossing-Over.

The members of a linked group may not always be completely linked as in the case just given. In fact, in the F_1 female from the same cross, some of the recessive characters of one series may be interchanged for wild type characters from the other series, but even then, since they remain united more often than they interchange, they are still said to be linked together. This interchange is called crossing-over, which means that, between two corresponding linked series, there may take place an orderly interchange involving great numbers of genes. Since an understanding of this process is essential to what follows, a few examples of crossing-over may be given.

When a male Drosophila with the two recessive mutant characters, yellow wings and white eyes, is mated to a female with the wild type characters, gray wings and red eyes, the daughters and sons have gray wings and red eyes (Fig. 11). If one of the daughters is mated to a male with the two recessive characters, yellow wings and white eyes, there are four kinds of offspring. Two kinds are like the grandparents, that is, they have yellow wings and white eyes, or gray wings and red eyes. Together they constitute 99 per cent of the offspring. The characters that went in together have come out together in a much higher percentage than expected from Mendel's second

.w, *viz.*, the law of free assortment. In addition to the vo classes, there are two other kinds of flies in the second eneration (Fig. 11), one with yellow wings and red yes, and the other with gray wings and white eyes. ogether they constitute 1 per cent of this generation.

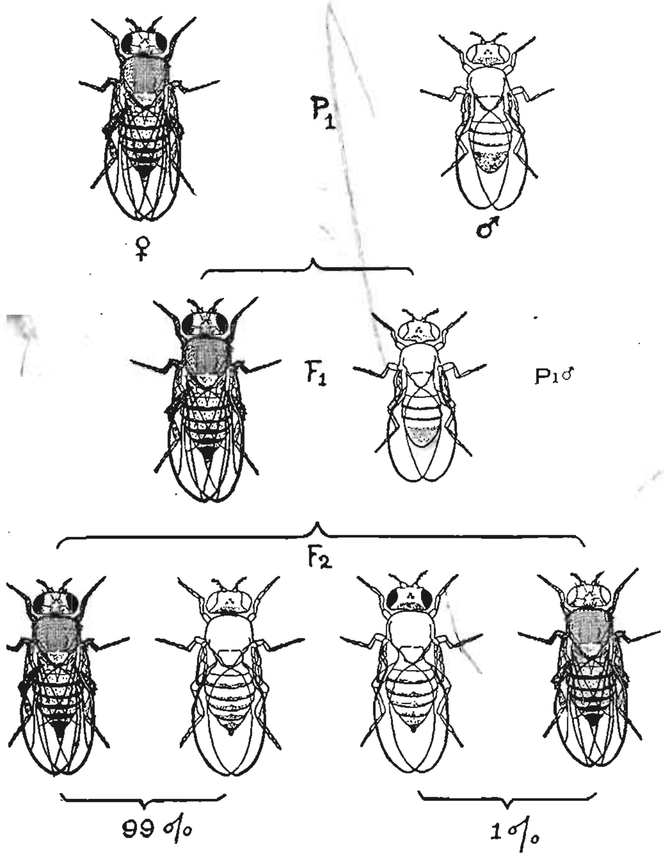


FIG. 11.

ıe inheritance of two recessive sex-linked characters, *viz.*, white es and yellow wings and their "normal" allelomorphs, *viz.*, d eyes and gray wings.

They are the crossovers, and represent interchanges between the two linkage groups.

A similar experiment can be made in which the same characters as before are differently combined. If a male Drosophila with yellow wings and red eyes is mated to a

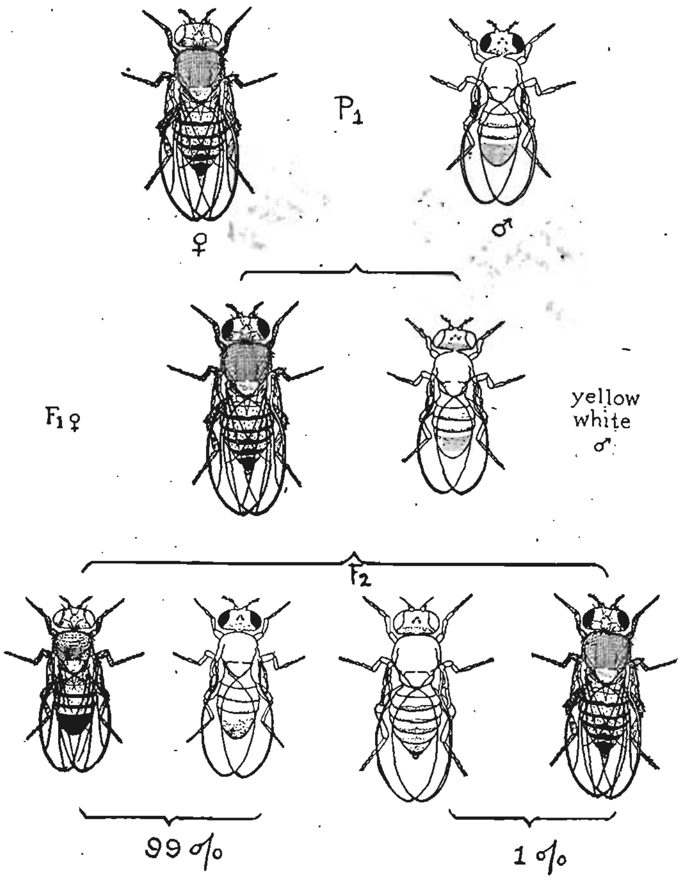


FIG. 12.

The inheritance of the same two sex-linked characters of Fig. 11, but in reciprocal combinations, *viz.*, red eyes and yellow wings, and white eyes and gray wings.

female with gray wings and white eyes the daughters have gray wings and red eyes (Fig. 12). If one of the daughters is mated to a male with the two recessive mutant characters, yellow wings and white eyes, there are four kinds of flies produced. Two of these are like the two grandparents, and constitute 99 per cent of the output. Two are new combinations, or crossovers, one with yellow wings and white eyes and the other with gray wings and red eyes. Together they make up 1 per cent of the second generation.

These results show that the same amount of crossing-over takes place irrespective of the way in which the combinations of the same characters enter the cross. If the two recessives enter together, they tend to hold together. This relation was called coupling by Bateson and Punnett. If one of the recessives enters from one parent and the other recessive from the other parent, they tend to come out separately (each in combination with the dominant that went in with it). This relation was called repulsion. It is clear, however, from the two crosses that have just been given, that these relations are not two phenomena, but expressions of the same one, namely, that the two linked characters that enter a cross, quite irrespective of their dominance or recessiveness, tend to hold together.

Other characters give different percentages of crossing-over. For example, when a male Drosophila with the two mutant characters, white eyes and miniature wings (Fig. 13), is mated to a wild type fly with red eyes and long wings the offspring have long wings and red eyes. If one of the daughters is mated to a male with white eyes and miniature wings the offspring are of four kinds. The two grandparental types constitute 67 per cent and the two cross-over types 33 per cent of this generation.

A still higher percentage of crossing-over is given in

the following experiment. A male with white eyes and forked bristles is mated to a wild type female (Fig. 14). The offspring have red eyes and straight bristles. If one of the daughters is mated to a male with white eyes and forked bristles, there are four kinds of individuals pro-

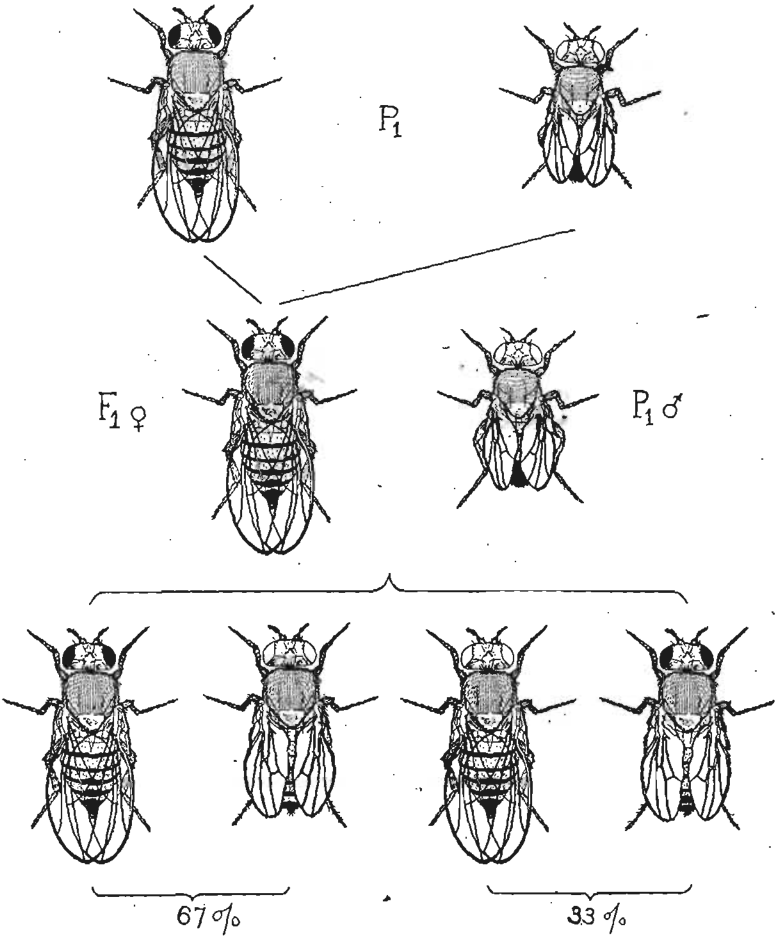


FIG. 13.

The inheritance of two sex-linked characters, white eyes and miniature wings, and red eyes and long wings.

duced. The grandparental types constitute 60 per cent and the crossovers 40 per cent of this second generation.

A study of crossing-over has shown that all possible percentages of crossing-over occur, up to nearly 50 per cent. If exactly 50 per cent of crossing-over took place,

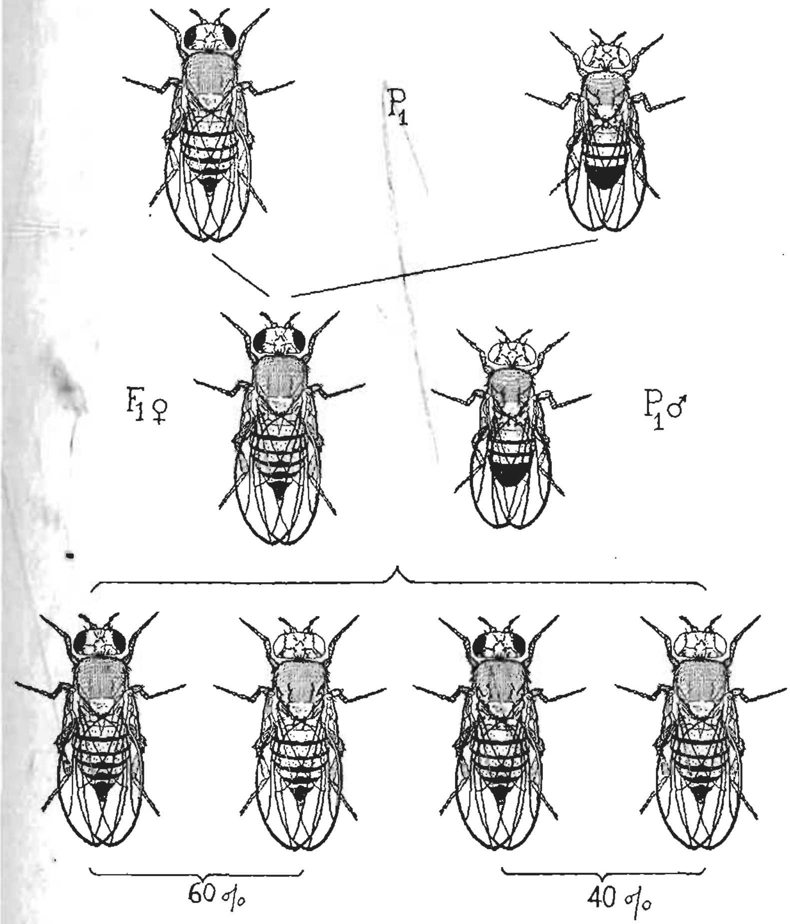


FIG. 14.
The inheritance of two sex-linked characters, white eyes and forked bristles, and red eyes and normal bristles.

the numerical result would be the same as when free assortment occurs. That is, no linkage would be observed even though the characters involved are in the same linkage group. Their relation as members of the same group could, nevertheless, be shown by their common linkage to some third member of the series. If more than 50 per cent crossing-over should be found, a sort of inverted linkage would appear, since the cross-over combinations would then be more frequent than the grandparental types.

The fact that crossing-over in the female of Drosophila is always less than 50 per cent, is due to another correlated phenomenon called double crossing-over. By double crossing-over is meant that interchange takes place twice between two pairs of genes involved in the cross. The result is to lower the *observed* cases of crossing-over, since a second crossing-over undoes the effect of a single crossing-over. This will be explained later.

The Simultaneous Interchange of Many Genes in Crossing-Over.

In the examples of crossing-over just given, two pairs of characters were studied. The evidence involved only those cases of crossing-over that took place once between the two pairs of genes involved in the cross. In order to obtain information as to how frequently crossing-over takes place elsewhere, *i.e.*, in the rest of the linkage group, it is necessary to include pairs of characters that cover the entire group. For example, if a female with the following nine characters of Group I, scute, echinus, cross-veinless, cut, tan, vermilion, garnet, forked and bobbed, is crossed to a wild type male, and if the F_1 female (Fig. 15) is back-crossed to the same multiple recessive type, the offspring produced will give a record of every crossing-over. If crossing-over had taken place

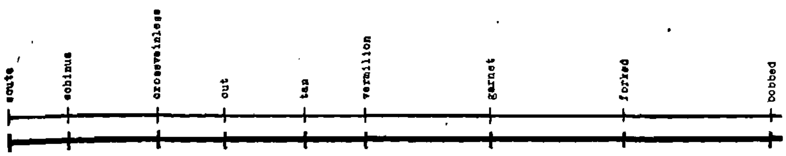


FIG. 15.
Diagram of two allelomorphic series of linked genes. In the upper line the approximate location of nine, sex-linked recessive genes is indicated. In the lower line the normal allelomorphic genes are indicated.

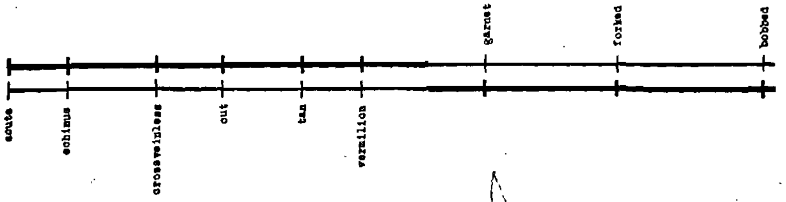


FIG. 16.
Diagram to show crossing-over between garnet and vermilion, *i.e.*, near the middle of the series shown in Fig. 15.

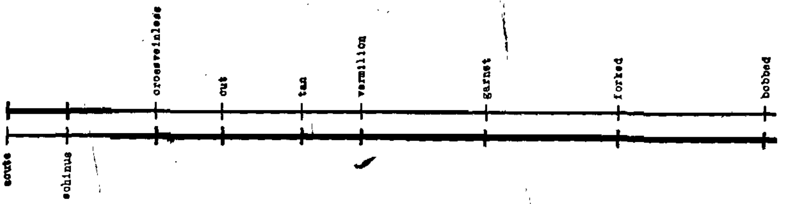


FIG. 17.
Diagram to show crossing-over between echinus and cross-veinless near the left end of the series. See Fig. 15.

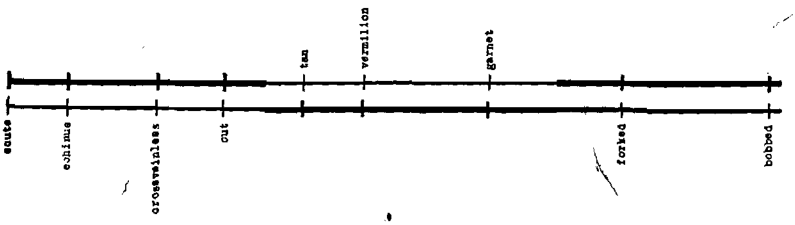


FIG. 18.
Double crossing-over between the two series of genes indicated in Fig. 15. One crossing-over is between cut and tan and the other between garnet and forked.

near the middle of the series (between vermilion and garnet), the result would be that shown in Fig. 16. Two complete halves have interchanged.

In other cases, crossing-over may take place near one end (for example, between echinus and cross-veinless). The result is like that shown in Fig. 17. Only the short ends of the two series have interchanged. The same kind of process occurs whenever an interchange takes place. Whole series of genes are interchanged, although as a rule the interchange is noticed only between the genes on each side of the crossing-over.

When simultaneous crossing-over occurs at two levels at the same time (Fig. 18) very many genes are also involved. For example, in the series just given one crossing-over is supposed to take place between cut and tan, and another crossing-over between garnet and forked. All the genes in the middle of the two series have been interchanged. This would pass unobserved were there no mutant genes in the region to indicate the fact that two crossings-over had taken place, since the two ends of both series remain the same as before.

The Linear Order of the Genes.

It is self-evident that if two pairs of genes should be near together, the chance that crossing-over occurs between them is smaller than if they are further apart. If two other genes are still further apart the chance of crossing-over is correspondingly increased. We may utilize these relations to obtain information as to the "distance" at which any two pairs of elements lie with respect to each other. With this information we can construct charts of the series of elements in each of the linkage groups. This has been done for all the linkage groups of Drosophila. Such a chart (Fig. 19) gives the result as far as carried out.

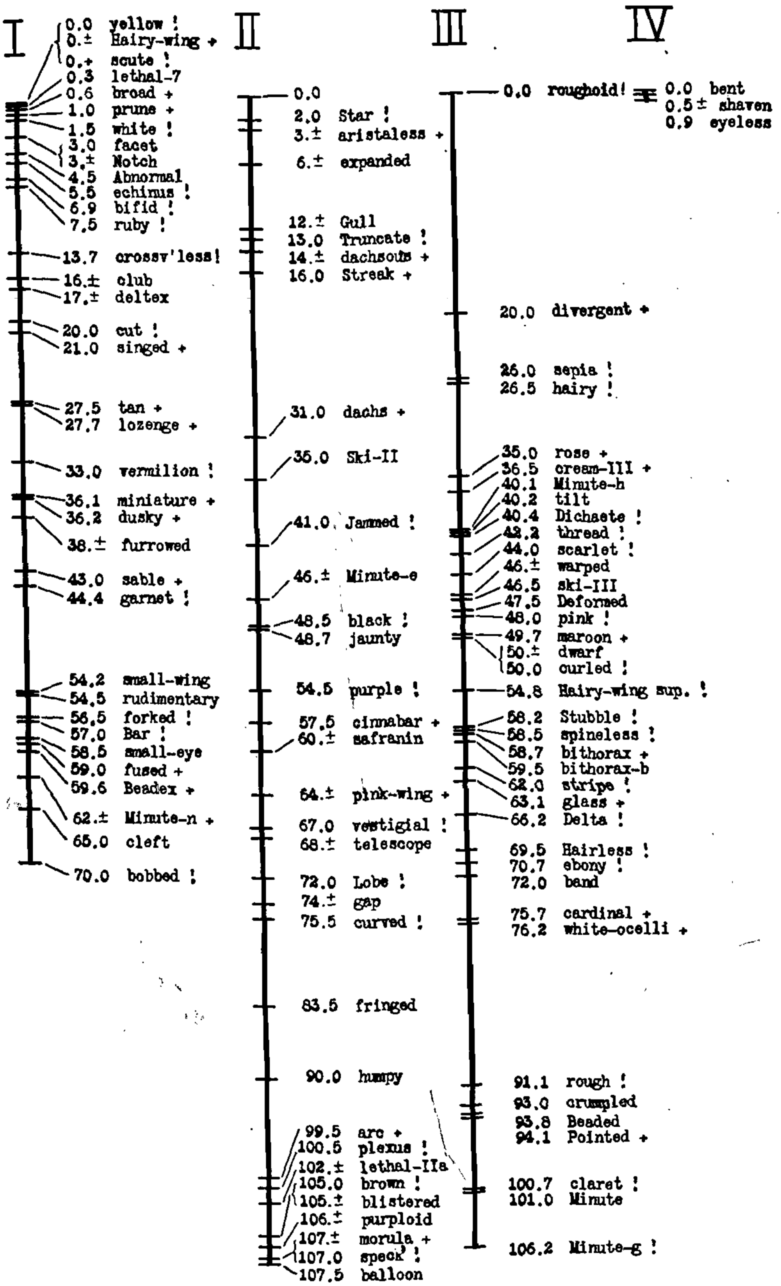


FIG. 19.

Map or chart of the four series, I, II, III, IV, of linked genes of Drosophila melanogaster. The "map distance" is given in the

In the preceding illustrations of linkage and crossing-over, that have been given, the genes are represented as lying in a line—like beads on a string. The numerical data from crossing-over show, in fact, that this arrangement is the only one that is consistent with the results obtained, as the following example will serve to illustrate.

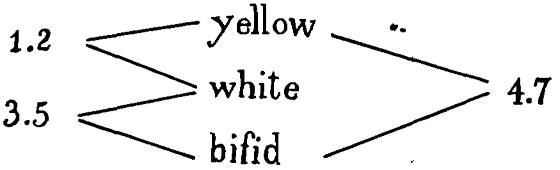


Fig. 20.

Diagram illustrating the linear order of three sex-linked genes, *viz.*, yellow wings, white eyes, bifid wings.

Suppose that crossing-over between yellow wings and white eyes occurs in 1.2 per cent of cases. If we then test white with a third member of the same series, such as bifid wings, we find 3.5 per cent of crossing-over (Fig. 20). If bifid is in line and on one side of white it is expected to give with yellow 4.7 per cent crossing-over, if on the other side of white it is expected to give 2.3 per cent of crossing-over with yellow. In fact, it gives one of these values, namely, 4.7. We place it, therefore, below white in the diagram. This sort of result is obtained whenever a new character is compared with two other members of the same linkage group. The crossing-over of a new character is found to give, in relation to two other known factors, either the sum or the difference of their respective cross-over values. This is the known relation of points on a line, and is the proof of the linear order of the genes; for no other spatial relation has yet been found that fulfills these conditions.

The Theory of the Gene.

We are now in a position to formulate the theory of the gene. *The theory states that the characters of the individual are referable to paired elements (genes) in the germinal material that are held together in a definite number of linkage groups; it states that the members of each pair of genes separate when the germ-cells mature in accordance with Mendel's first law, and in consequence each germ-cell comes to contain one set only; it states that the members belonging to different linkage groups assort independently in accordance with Mendel's second law; it states that an orderly interchange—crossing-over—also takes place, at times, between the elements in corresponding linkage groups; and it states that the frequency of crossing-over furnishes evidence of the linear order of the elements in each linkage group and of the relative position of the elements with respect to each other.*

These principles, which, taken together, I have ventured to call the theory of the gene, enable us to handle problems of genetics on a strictly numerical basis, and allow us to predict, with a great deal of precision, what will occur in any given situation. In these respects the theory fulfills the requirements of a scientific theory in the fullest sense.

CHAPTER II

PARTICULATE THEORIES OF HEREDITY

THE evidence given in the last chapter led to the conclusion that there are hereditary units in the germinal material that are, to a greater or less extent, independently sorted out between successive generations of individuals. Stated more accurately, the independent reappearance in later generations of the characters of two individuals combined in a cross can be explained by the theory of independent units in the germinal material.

Between the characters, that furnish the data for the theory, and the postulated genes, to which the characters are referred, lies the whole field of embryonic development. The theory of the gene, as here formulated, states nothing with respect to the way in which the genes are connected with the end-product or character. The absence of information relating to this interval does not mean that the process of embryonic development is not of interest for genetics. A knowledge of the way in which the genes produce their effects on the developing individual would, no doubt, greatly broaden our ideas relating to heredity, and probably make clearer many phenomena that are obscure at present, but the fact remains that the sorting out of the characters in successive generations can be explained at present without reference to the way in which the gene affects the developmental process.

There is, nevertheless, a fundamental assumption implied in the statement just made, *viz.*, that the developmental process follows strictly causal laws. A change in a

gene produces definite effects on the developmental processes. It affects one or more of the characters that appear at some later stage in the individual. In this sense, the theory of the gene is justified without attempting to explain the nature of the causal processes that connect the gene and the characters. Some needless criticism of the theory has arisen from failure to clearly understand this relation.

It has been said, for example, that the assumption of invisible units in the germ-materials really explains nothing, since to these are ascribed the very properties that the theory sets out to explain. In fact, however, the only properties ascribed to the gene are those given in the numerical data supplied by the individuals. This criticism, like others of its kind, arises from confusing the problems of genetics with those of development.

Again, the theory has been unfairly criticised on the grounds that the organism is a physico-chemical mechanism, while the genetic theory fails to account for the mechanism that is involved. But the only assumptions made by the theory, the relative constancy of the gene, its property of multiplying itself, the union of the genes and their separation when the germ-cells mature, involve no assumptions inconsistent with physical principles, and while it is true the physical and chemical processes involved in these events cannot be explicitly stated, they relate at least to phenomena that we are familiar with in living things.

A part of the criticism of Mendel's theory arises from a failure to appreciate the evidence on which the theory rests, and also from a failure to realize that its procedure is different from that which, in the past, has led to the formulation of other particulate theories of heredity and of development. There have been a good many of these theories, and biologists have become, through ex-

perience, somewhat incredulous in respect to any and all theories that postulate invisible units. A brief examination of a few of the earlier speculations may serve to make the difference between the old and the new procedure more apparent.[1]

Herbert Spencer's theory of physiological units, proposed in 1863, assumes that each species of animal or plant is composed of fundamental units that are all alike for each species. The elements concerned are supposed to be larger than protein molecules and more complex in structure. One of the reasons that led Spencer to this view is that any part of the organism may in certain cases reproduce the whole again. The egg and the sperm are such fragments of the whole. The diversity of structure in each individual is vaguely ascribed to a "polarity" or some sort of crystal-like arrangement of the elements in different regions of the body.

Spencer's theory is purely speculative. It rests on the evidence that a part may produce a new whole like itself, and infers from this that all parts of the organism contain material out of which a new whole may develop, but, while this is, in part, true, it does not follow that the whole must be made up of a single kind of unit. Our modern interpretation of the ability of a part to develop into a new whole must also assume that each such part contains the elements for the construction of a new whole, but these elements may be different from each other, and to this system the differentiation of the body is referred. So long as a complete set of units is present, the power to produce a new whole is potentially given.

Darwin's theory of pangenesis, proposed in 1868, appealed to a host of different invisible particles. The theory states that minute representative elements, called

[1] A full discussion of earlier theories is given by Delage in *Heredité* and by Weismann in the *Germ-Plasm*.

gemmules, are being continually thrown off from every part of the body. Those that reach the germ-cells become incorporated there with the hereditary units of the same general kind already present.

The theory was proposed primarily to explain how acquired characters are transmitted. If specific changes in the body of the parent are transmitted to the offspring, some such theory is required. If the changes in the body are not transmitted, there is no need of such a theory.

Weismann in 1883 challenged the entire transport theory, and convinced many, but not all, biologists that the evidence for the transmission of acquired characters was inadequate. This led him to develop his theory of the isolation of the germ-plasm. The egg produces not only a new individual, but other eggs like itself, carried by the new individual. The egg produces the individual, but the individual has no subsequent influence on the germ-plasm of the eggs contained in it, except to protect and to nourish them.

From this beginning Weismann developed a theory of particulate inheritance of representative elements. He appealed to evidence derived from variation, and he extended his theory to include a purely formal explanation of embryonic development.

We are concerned, in the first place, with Weismann's views as to the nature of the hereditary elements or *ids* as he calls them. The ids he identified in his later writings as small chromosomes when many small chromosomes are present, but when only a few chromosomes are present he supposed that each is made up of several or many ids. Each id contains all the elements that are essential to the development of a single individual. Each is a microcosm. The ids differ from each other in that they are the representatives of ancestral individuals or germ-

plasms, each different from the others in one or another way.

The individual variations shown by animals are due to the different recombinations of ids. This is brought about by the union of eggs and sperms. The number of ids would become indefinitely large were it not that, at the ripening of the germ-cells, the number of ids is reduced to half.

Weismann also formulated an elaborate theory of embryonic development based on the idea that the ids are separated into their smaller elements as the egg divides, until, finally, each kind of cell in the body comes to contain one of the ultimate components of the ids, *i.e.*, determinants. In the cells destined to become germ-cells the disintegration of the ids does not take place. Hence the continuity of the germ-plasm, or of the colony of ids. The application of his theory to embryonic development lies outside the modern theory of heredity that either ignores the developmental process, or else postulates a view exactly the opposite of that of Weismann, namely, that in every cell of the body the entire heredity complex is present.

It will be seen without further elaboration that Weismann's ingenious speculation invokes, in order to explain variation, processes that are akin to those we adopt today. Variation, he believed, is due to the recombination of units from the parents. These are reduced to half in the process of maturation of the egg and sperm. The units are wholes and each represents an ancestral stage.

We owe to Weismann largely the idea of the isolation and continuity of the germinal material. His challenge of the Lamarckian theory was of immense service to clear thinking. The theory of the inheritance of acquired characters had obscured for a long time all problems dealing with heredity. Weismann's writings were also

unquestionably important in keeping in the foreground the intimate relation between heredity and cytology. It is difficult for us to estimate to what extent his fascinating speculations have influenced our later attempts to interpret heredity in terms of chromosome constitution and behavior.

These and other earlier speculations have today mainly an historical interest. They do not represent the main path along which the modern theory of the gene has developed, which rests its claims to recognition on the method by which it is derived and on its ability to predict exact numerical results of a specific kind.

I venture to think that, however similar to the older theories the modern theory may appear, it stands apart from them, in that it has arisen step by step from experimentally determined genetic evidence that has been carefully controlled at every point. The theory need not and does not, of course, pretend to be final. It will, no doubt, undergo many changes and improvements in new directions, but most of the facts concerning heredity, known to us at present, can be accounted for by the theory as it stands.

CHAPTER III

THE MECHANISM OF HEREDITY

THE statement of the theory of the gene at the en
of the first chapter is derived from purely numeri
cal data without respect to any known or assume
changes in the animal or plant that bring about, in th
way postulated, the distribution of the genes. Howeve
satisfactory the theory may be in this respect, biologist
will seek to discover in the organism how the orderl
redistribution of the genes takes place.

During the last quarter of the last century, and con
tinuously through the first quarter of the present centur
the study of the changes that take place during the fina
stages in the maturation of the egg and sperm-cell hav
revealed a remarkable series of events that go far towar
furnishing a mechanism of heredity.

It was discovered that there is a double set of chromo
somes in each cell of the body and in the early stages o
the germ-cells. The evidence of this duality came fro
observations on differences in the sizes of the chromo
somes. Whenever recognizable differences exist there ar
two chromosomes of each kind in the somatic cells an
one of each in the germ cells after maturation. One mem
ber of each kind has been shown to come from the fathe
and the other from the mother. At the present time th
duality of the chromosome complex is one of the bes
established facts of cytology. The only striking exceptio
to the rule is sometimes found in the sex-chromosome
but even here the duality holds for one sex, and often fo
both.

The Mechanism of Mendel's Two Laws.

Toward the end of the ripening period of the germ-cells, chromosomes of the same size come together in pairs. This is followed by a division of the cell, when the members of each pair go into opposite cells. Each mature germ-cell comes to contain only one set of chromosomes, (Figs. 21 and 22).

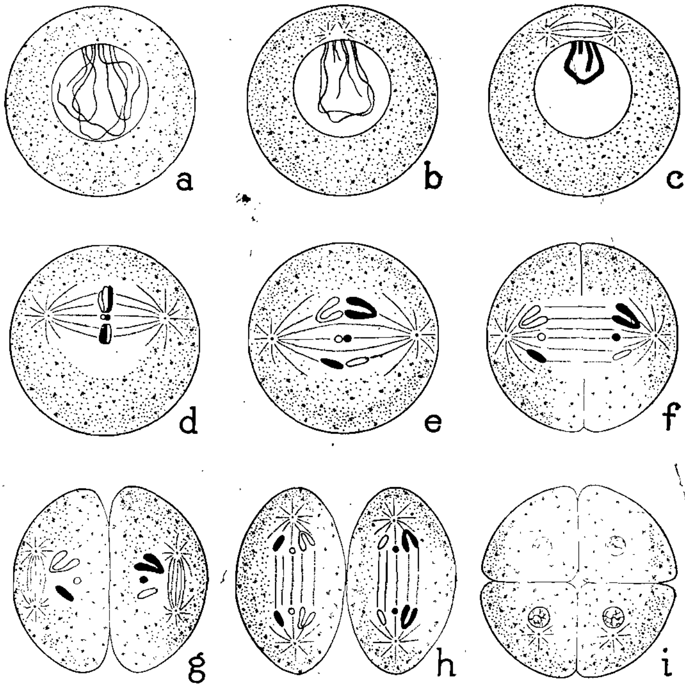


FIG. 21.

Diagram of the two maturation divisions of sperm-cells. Three pairs of chromosomes are represented; those from the father in black, those from the mother in white (except in a, b, c). The first maturation division, here the reduction division, is shown in d, e, f. The second, or equational division, in which each chromosome splits lengthwise into two daughter chromosomes, is shown in g, h.

This behavior of the chromosomes in the maturation stages parallels Mendel's first law. A chromosome derived from the father separates from a chromosome derived from the mother for each pair of chromosomes. The

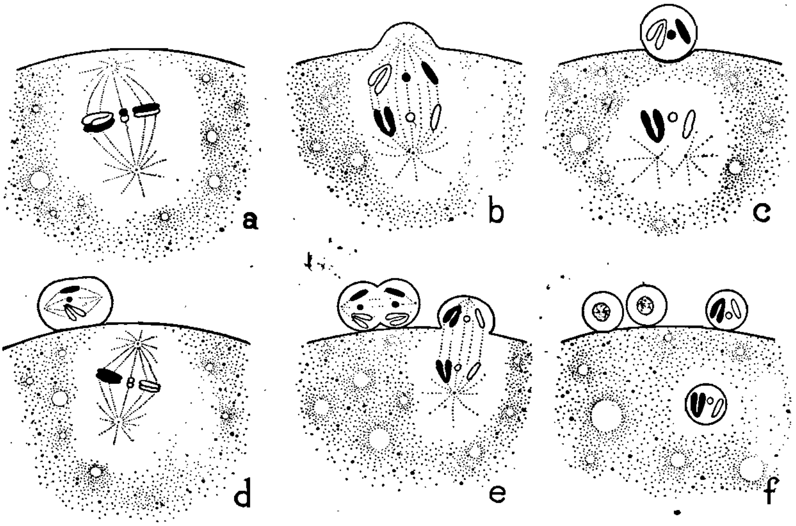


Fig. 22.

Diagram of two maturation divisions of the egg. The first polar spindle is shown in a. The separation of the paternal and maternal chromosomes (reduction) is shown in b. The first polar body has been given off in c. The second polar spindle is formed in d; each chromosome has split lengthwise into daughter halves (equational division). The second polar body is being given off in e. The egg-nucleus is left in f with the half (haploid) number of chromosomes.

germ-cells that result contain one chromosome of each kind. Taking the chromosomes in pairs we may say, half of the germ-cells, when mature, contain one member of each pair, the other half the mates of those chromosomes, pair for pair. If one substitutes Mendelian units for chromosomes, the statement is the same.

One member of each pair of chromosomes comes from the father, its mate from the mother. If, when the conjugants come to lie on the spindle, all the paternally derived chromosomes were to go to one pole, and all the maternally derived to the other pole, the two resulting

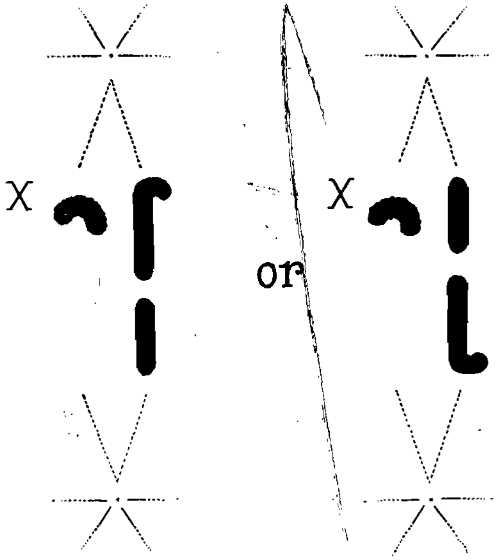


FIG. 23.

Diagram to illustrate the random assortment of a pair of chromosomes with respect to the X-chromosome. (After Carothers.)

germ-cells would be like those of the father and of the mother. There is no *a priori* reason for supposing that the conjugants would behave in this way, but it has been extremely difficult to prove that they do not do so, because from the very nature of the case, the conjugating chromosomes being alike in shape and size, it is not as a rule possible to tell from observation which member is paternal, which maternal.

In recent years, however, a few cases have been found in grasshoppers where slight differences are sometimes

present between the members of certain pairs—differences in shape, or in the attachment to the spindle fibers (Fig. 23). When the germ-cells mature these chromosomes conjugate and then separate. Since they retain their individual differences, they can be traced to the poles.

Now in these grasshoppers there is, in the male, an unpaired chromosome that is connected with sex determination (Fig. 23). It passes at the maturation division to one pole or to the other. It serves as a land-mark for the other pairs of chromosomes. Miss Carothers, who first made these observations, found that a marked pair (one bent, one straight) separates at random with respect to the sex chromosome.

Carrying the matter further, other chromosome pairs were found to show at times constant differences in some individuals. A study of these chromosome pairs at reduction has shown, again, a random distribution of the members of the pairs with respect to one another. Here then we have objective evidence of the independent assortment of the pairs of chromosomes. This evidence parallels Mendel's second law, which calls for independent distribution of the members of different linkage groups.

The Number of the Linkage Groups and the Number of the Chromosome Pairs.

Genetics has shown that the hereditary elements are *linked* in groups, and in one case with certainty, and in several other cases with some probability, there is a definite and fixed number of these linkage groups. In Drosophila there are only four such groups, and there are four pairs of chromosomes. In the sweet pea there are seven chromosome pairs (Fig. 24), and probably seven independent pairs of Mendelian characters have been found by Punnett. In the edible pea there are also seven pairs

of chromosomes (Fig. 24) and seven independent pairs of Mendelian characters, according to White. In Indian corn there are ten to twelve (?) pairs of chromosomes, and several groups of linked genes have been detected. In the snapdragon, with sixteen pairs of chromosomes, the number of independent genes approaches the number of the chromosomes. In other animals and plants, also, linked genes have been reported, but as yet this number is small in comparison with the chromosome numbers.

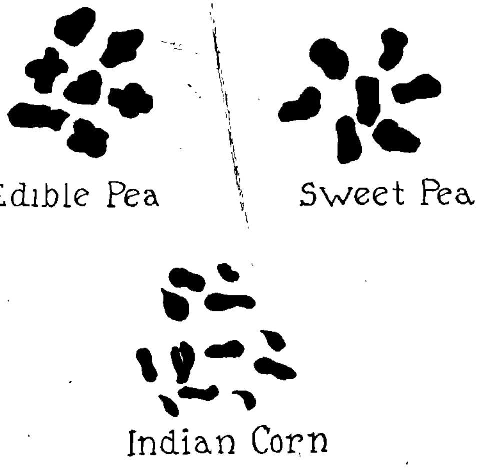


FIG. 24.

The reduced number of chromosomes in the edible pea (n=7), sweet pea (n=7), and Indian corn (n=10 or 12?).

The further fact that, to date, no case is known where there are more independently assorting pairs than there are pairs of chromosomes is further evidence, as far as it goes, in favor of the view that the linkage groups and the chromosomes correspond in number.

The Integrity and Continuity of the Chromosomes.

The integrity of the chromosomes, or their continuity from one cell generation to the next, is also essential for

the chromosome theory. There is general agreement amongst cytologists that when the chromosomes are set free in the protoplasm they remain intact through the entire period of cell division, but when they take up fluid and combine to form the resting nucleus, it is no longer possible to trace their history. By indirect means, however, it has been possible to get some evidence as to the conditions of the chromosomes in the resting stages.

After each division the individual chromosomes become vacuolated as they come together to form a new resting nucleus. They can be followed for some time, forming separate compartments of the single nucleus that re-forms. They then lose their staining quality and can no longer be identified. When the chromosomes are again about to appear, sac-like bodies are seen. This suggests, if it does not prove, that the chromosomes have remained in place during the resting stage.

Boveri showed that when egg-cells of Ascaris divide, the *daughter* chromosomes of each pair are pulled apart in the same way, and often show characteristic shapes (Fig. 25). At the next division of such cells, when the chromosomes of daughter cells are about to reappear, they show similar arrangements of their threads. The inference is clear. The threads retain in the resting nucleus the shapes that they had when they entered the nucleus. This evidence is favorable to the view that the chromosomes have not passed into solution, and later reformed, but have retained their integrity.

Finally, there are cases where the chromosome numbers have been increased, either by becoming doubled, or by crossing species with different numbers of chromosomes. There may be, then, three or four chromosomes of each kind. The same number is retained as a rule through all successive divisions.

On the whole, then, while the cytological evidence does

not demonstrate completely that the chromosomes remain intact throughout their history, the evidence, as far as it goes, is favorable to this view.

There is, however, a very important limitation that must be placed on this statement. The genetic evidence clearly proves that between the members of the same pair of chromosomes there is at times an orderly interchange of parts. Does the cytological evidence show any indication of such an interchange? Here we enter on more questionable ground.

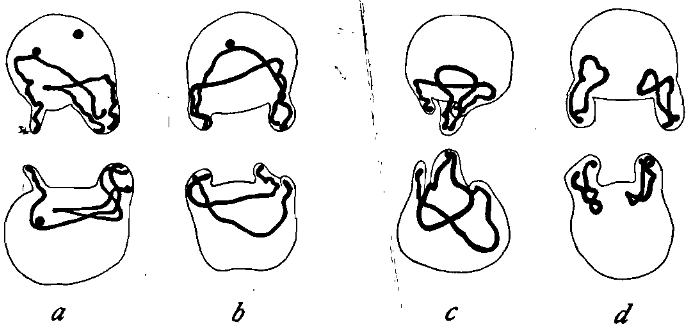


FIG. 25.

The nuclei of four pairs of sister cells (above and below) showing the position of the daughter chromosomes as they come out of the resting nuclei. (After Boveri.)

Mechanism of Crossing-Over.

If, as other evidence clearly shows, the chromosomes are the bearers of genes, and if the genes may interchange between members of the same pair, it follows that sooner or later we may expect to find some kind of mechanism by which such interchange takes place.

Several years before the genetic discovery of crossing-over, the process of conjugation of the chromosomes, and their reduction in number in the mature germ cells had been fully established. It was demonstrated that at the

time of conjugation the members of the same pair of chromosomes are those that combine. In other words, conjugation is not at random, as one might possibly have inferred from the earlier accounts of the process, but conjugation is always between a paternally derived and a maternally derived specific chromosome.

We may now add to this information the following fact, namely, that conjugation takes place because the members of a pair are alike, not because they have come from a male and a female respectively. This has been shown in two ways. In hermaphroditic types the same union occurs, although, after self-fertilization, both members of each pair have come from the same individual. Secondly, in exceptional cases, the two members of a pair have come from the same egg, yet presumably they conjugate since crossing-over takes place.

The cytological evidence of the conjugation of like chromosomes supplies the first steps for a mechanical explanation as to how an interchange might take place, for, obviously, if the two members of each pair come to lie side by side throughout their length, gene to gene as it were, the chromosomes are brought into a position where equivalent blocks might be interchanged in an orderly way. Of course, it does not follow that in consequence of their side to side apposition an interchange would necessarily follow; in fact, a study of the crossing-over in a linkage group, such as the sex-linked group of genes of Drosophila (where a sufficient number of genes is present to furnish complete evidence of what takes place in the linkage series), shows that there is no interchange at all in about 43.5 per cent of the eggs for that pair of chromosomes. The same evidence shows that one interchange takes place in about 43 per cent of the eggs; that two interchanges take place in about 13 per cent (double crossing-over) and three interchanges in 0.5

per cent. In the Drosophila male, no interchange at all takes place.

In 1909 Janssens published a detailed account of a process that he called Chiasmatypie. Without entering here into the details of Janssens' work it may be stated that he brought forward evidence which he believed to show that there is an interchange of blocks or segments between the members of the conjugating pairs of chromosomes which is traceable to an earlier twisting of the two conjugating chromosomes around each other (Fig. 26).

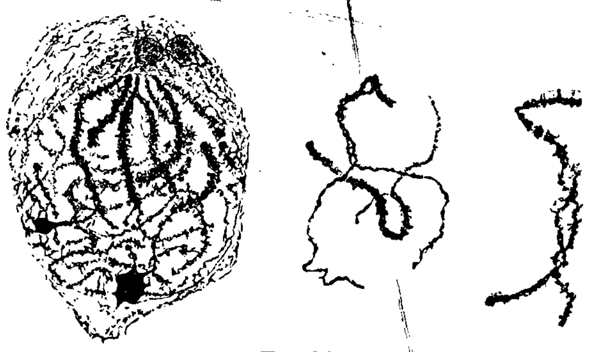


FIG. 26.

The conjugation of the chromosomes in Batrachoseps. The twisting of the two thin threads around each other is suggested in one of the two chromosomes in the middle figure. (After Janssens.)

Unfortunately there is scarcely any stage in the maturation divisions that is as much in dispute as this one involving the twisting of the chromosomes. From the nature of the case it is practically impossible to demonstrate, even when twisting of the chromosomes is admitted, that it actually leads to an interchange of the kind demanded by the genetic evidence.

There are many published figures of the chromosomes twisted about each other. But in some respects this evidence proves too much. For instance, the most familiar and best ascertained stage, where twisting is obviously present, is found at the time when the conjugant pairs are shortening preparatory to entrance into the equator of the spindle (Fig. 27). The usual interpretation of the

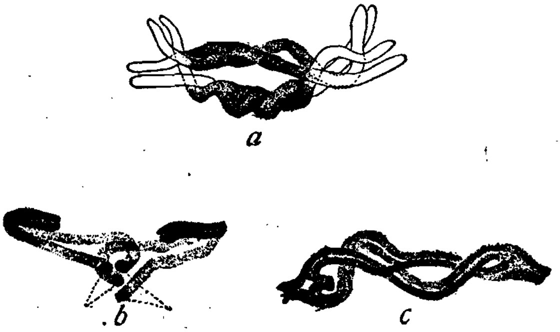


FIG. 27.

The late twisting of the thick threads (chromosomes) just before they enter the spindle of the first maturation division of Batrachoseps. (After Janssens.)

twisting at this stage is that it is in some way connected with the shortening of the two conjugants. There is nothing in these figures to show that this leads up to interchange. While it is possible that some of the cases of this kind may be due to an earlier twisting of the threads about each other, yet the persistence of the spiral would rather indicate that crossing-over had not taken place, for this would undo the twist.

If we turn next to the published drawings of the earlier stages we find a number of cases in which the thin threads (leptotene stage) are represented as though twisted

ıbout each other (Fig. 28b), but this interpretation is ›ften open to suspicion. It is extremely difficult, in fact, to letermine when threads as delicate as these come into ;ontact with each other whether they pass above or below, .*e.,* above at one node and below at the next, etc. The lifficulty is enormously enhanced by the coagulated condition of the threads, and it is only in this condition that they are stained for microscopic study.

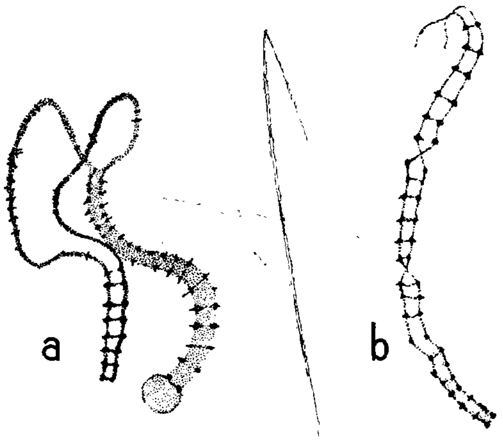


FIG. 28.

Conjugation of a pair of chromosomes of a planarian. In a, the two thin threads are coming together; in b, there are indications, at two levels, of crossing-over of the two united strands. (After Gelei.)

The preparations that most nearly approach a demonstration of the twisting of the leptotene threads are those in which the conjugation begins at one end (or at both ends of bent chromosomes) and progresses toward the other end (or toward the middle of the bend). The sperm-cells of Batrachoseps presents perhaps the most seductive preparations of this sort (Fig. 26), but the figures of Tomopteris are almost or quite as good. The drawings

of the eggs of Planaria (Fig. 28) are also quite convincing. Some at least of these figures give the impression that as the threads are coming together they overlap one or more times, but this impression is not sufficient to show that they do more than lie across each other as seen from certain levels. It does not follow moreover that they will interchange where they overlap. While it must be admitted, then, that the cytological evidence of crossing-over has not been demonstrated, and from the nature of the conditions it will be extremely difficult to actually prove; nevertheless, it has been shown in a number of cases that the chromosomes are brought into a position where such an interchange might readily be supposed to take place.

The cytologist, then, has given us an account of the chromosomes that fulfills to a degree the requirements of genetics. When we recall the fact that much of the evidence was obtained prior to the rediscovery of Mendel's paper, and that none of the work has been done with a genetic bias, but quite independently of what the students of heredity were doing, it does not seem probable that these relations are mere coincidences, but rather that students of the cell have discovered many of the essential parts of the mechanism by which the hereditary elements are sorted out according to Mendel's two laws and are interchanged in an orderly way between members of the same pair of chromosomes.

CHAPTER IV

CHROMOSOMES AND GENES

NOT only do the chromosomes pass through a series of manœuvres that go far toward supplying a mechanism for the theory of heredity, but from other sources evidence has accumulated supporting the view that the chromosomes are the bearers of the hereditary elements or genes, and this evidence has steadily grown stronger each year. The evidence comes from several sources. The earliest indication came from the discovery that the male transmits equally with the female. In animals, the male contributes, as a rule, only the head of the spermatozoön, which contains almost exclusively the nucleus composed of the condensed chromosomes. Although the egg contributes all the visible protoplasm of the future embryo, it has no preponderating influence on development, except so far as the beginning stages of development are determined by the egg protoplasm that has been under the influence of the maternal chromosomes. Despite this initial influence, which can be entirely ascribed to the previous influence of its own chromosomes, the later stages of development and the adult show no preponderance of maternal influence.

This evidence from the mutual influence of the two parents is not, however, in itself convincing, for, dealing with elements that are ultramicroscopical, it might be claimed that the sperm contributes something more than its chromosomes to the future embryo. In fact, in recent years it has been shown that visible protoplasm elements, the centrosomes, may possibly be brought into the egg by

the sperm. It has not been established, however, that the centrosomes have any specific effects on the developmental process.

From another quarter the significance of the chromosomes was shown. When two (or more) sperms enter the egg, the three sets of chromosomes that result may be distributed irregularly at the first division of the egg. Four instead of two cells, as in normal development, are formed. It has been shown by a detailed study of such eggs, combined with a study of the development of each of the isolated quarters, that normal development does not take place unless at least one full set of chromosomes is present. At least this is the most reasonable interpretation of the results. Since in these cases the chromosomes are not marked, the evidence does not do more than create a presumption that at least one full set of chromosomes must be present.

More recently still evidence in favor of such an interpretation has come from other sources. It has been shown, for example, that one set of chromosomes alone (haploid) is capable of producing an individual which, to a large extent, is a replica of the normal form, but this evidence also indicates that these haploid individuals are not as vigorous as the normal diploid type of the species. While this difference may depend on factors other than the chromosomes, the presumption remains that two sets of chromosomes are better than one, as things stand. On the other hand, in mosses, where there is a haploid stage in the life cycle, the artificial transformation of the haploid stage into a diploid stage does not appear to give an advantage. Furthermore, it remains to be shown that twice the number of chromosomes present in artificial tetraploids confers any advantage over the normal diploid set. It is evident, then, that we must be cautious as to the merits of one, two, three, or four sets of chromo-

›mes, especially when suddenly an artificial situation is ·eated by increasing or decreasing the normal comple- ent of chromosomes to which the machinery of develop- ent is already adjusted.

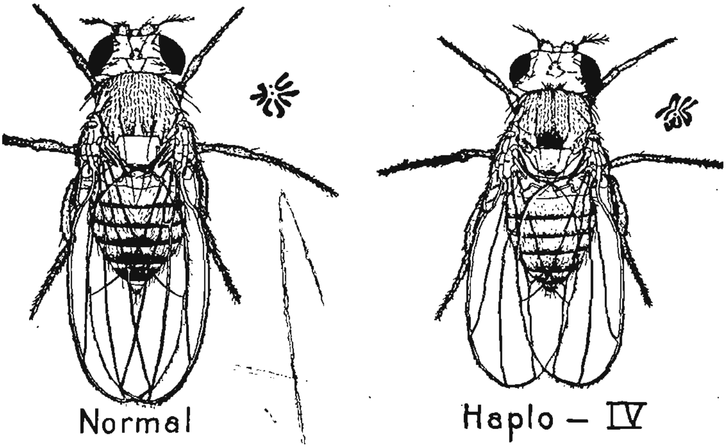


FIG. 29.

Normal and haplo-IV flies of Drosophila melanogaster. Their respective chromosome groups are shown above and to the right of each.

robably the most complete and convincing evidence ›erning the significance of the chromosomes in hered- ıas come from the recent genetic results that have to vith the specific effects of changes in the number of chromosomes where each one carries genetic factors enable us to identify its presence.

ecent evidence of this kind comes from the loss or n the addition of one of the small fourth chromosomes ›rosophila (chromosome-IV). It has been shown both ;enetic and cytological methods that chromosome-IV ometimes lost from one of the germ-cells—egg or ·m. If an egg lacking this chromosome is fertilized by

a normal sperm, the fertilized egg contains only one of the fourth chromosomes. It develops into a fly ("haplo-IV") *that shows in many parts of its* body slight differences from the normal fly (Fig. 29).

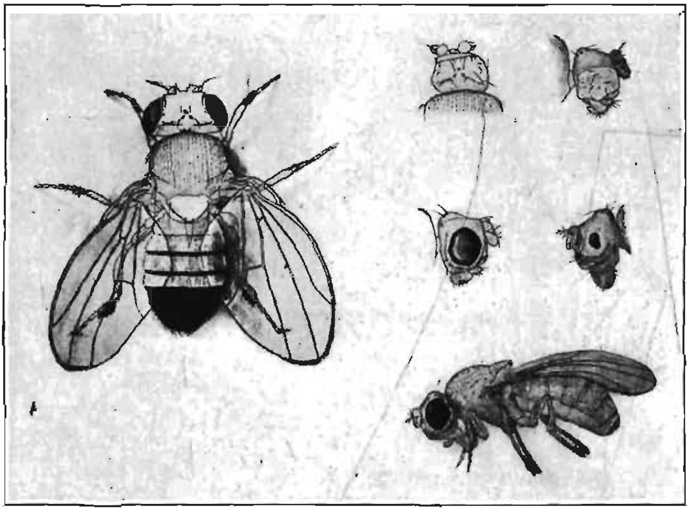


FIG. 30.

Characters in the fourth linkage group of D. melanogaster. To the *left, bent wings; to the right (above), four heads showing "eye*less," one in dorsal, three in side view; below, and to the right, shaven.

The result shows that specific effects are produce vhen one of these chromosomes is absent, even in tl resence of the other fourth chromosome.

There are three mutant elements or genes in this chr nosome, namely, eyeless, bent, shaven (Fig. 30). All thre re recessives. If a haplo-IV female is mated to a diploi yeless male with two fourth chromosomes (each rip perm with one) some of the offspring that hatch ar yeless, and if the pupae that do not hatch are remove

from their pupa-cases and examined, more eyeless flies are detected. The eyeless fly has come from an egg that did not carry chromosome-IV and was fertilized by a sperm with chromosome-IV carrying the eyeless gene.

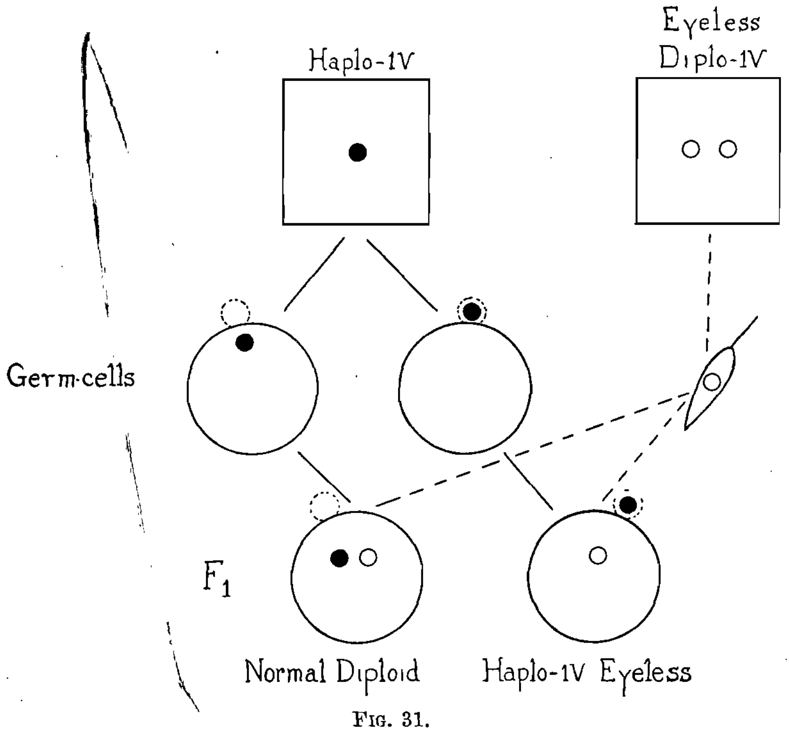


FIG. 31.

Diagram of a cross between a normal-eyed, haplo-IV fly, and an eyeless fly with two fourth chromosomes, each carrying a gene for eyeless. The fourth chromosome carrying the eyeless gene is here represented by an open circle, that for normal eyes by a black dot.

As shown in the diagram (Fig. 31), half of the flies should be eyeless, but most of these do not pass beyond the pupal stage, which means that the eyeless gene itself has a weakening effect on the individual, and that when to this is added the effects due to the absence of one of the fourth

triplo-IV is bred to an eyeless fly two kinds of offspring result (Fig. 33). Half are triplo-IV's, and half have the normal number of chromosomes, as shown in the diagram.

If, now, one of these triplo-IV flies is back-crossed to

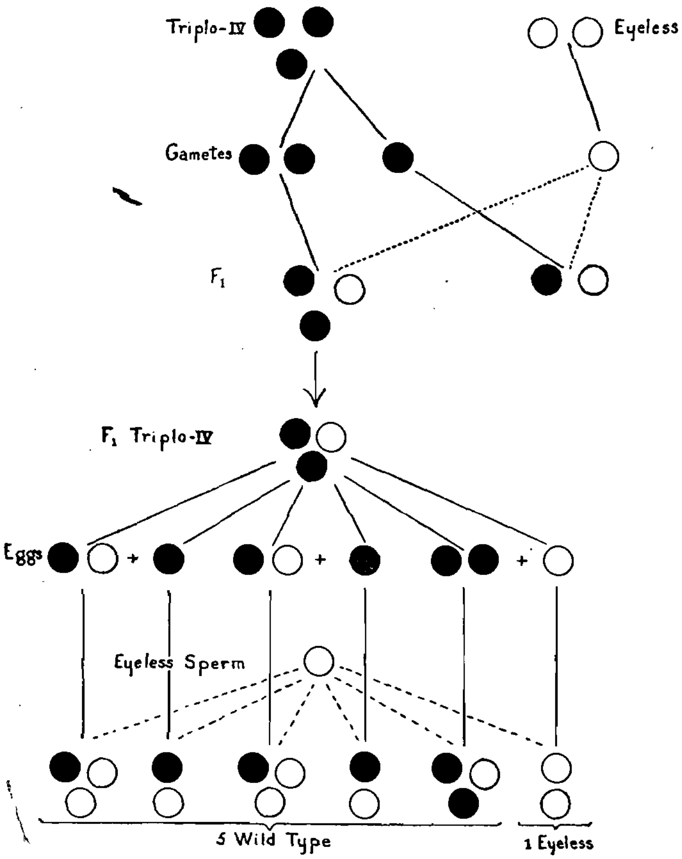


FIG. 33.

Diagram of a cross between a triplo-IV fly with normal eyes and normal diploid fly, pure for eyeless. In the lower half of the diagram an F_1 triplo-IV fly (whose gametes are represented in "F_1 eggs") is crossed to a diploid eyeless fly (whose "eyeless sperm" is represented by the open circle), giving five kinds of flies in the ratio of five wild type eyes to one eyeless.

an eyeless fly (from stock) the expectation is that there will be five wild-type flies to one eyeless (Fig. 33, lower half) instead of equality as in the ordinary case when a heterozygous individual is back-crossed to its recessive. The diagram (Fig. 33) shows the recombinations of germ-cells that are expected to give rise to the 5 to 1 ratio. The actual number of eyeless obtained approximates expectation.

These and other experiments of the same kind show that the genetic results check up at every point with the known history of chromosome-IV. No one familiar with the evidence can doubt for a moment that there is something in this chromosome that is responsible for the observed results.

There is also evidence that the sex-chromosomes are the bearers of certain genes. In Drosophila there are as many as 200 characters whose inheritance is said to be sex-linked. This term means only that they are carried by the sex-chromosomes. It does not mean that the characters are confined to one or the other sex. Owing to the differential pair of sex-chromosomes in the male, the X and the Y, the inheritance of characters whose gene lies in the X-chromosomes is somewhat different from that of any of the other characters. There is evidence that the Y-chromosome does not contain in Drosophila any genes that conceal the recessives in the X. It may, therefore, be ignored except in so far as it acts as the mate of the X in the male at the reduction division of the sperm-cells. The mode of inheritance of linked characters of Drosophila has already been given in Chapter I (Figs. 11, 12, 13, 14). The mode of transmission of the sex-chromosome is given in Fig. 38. An examination of the latter shows that these characters follow the known distribution of the chromosome.

Occasionally the sex-chromosomes "go wrong," and

this slip furnishes an opportunity to study the changes that take place in sex-linked inheritance. The most common disturbance is due to the failure of the two X's in the female to disjoin at one of the maturation divisions. The process is called non-disjunction. If an egg that has

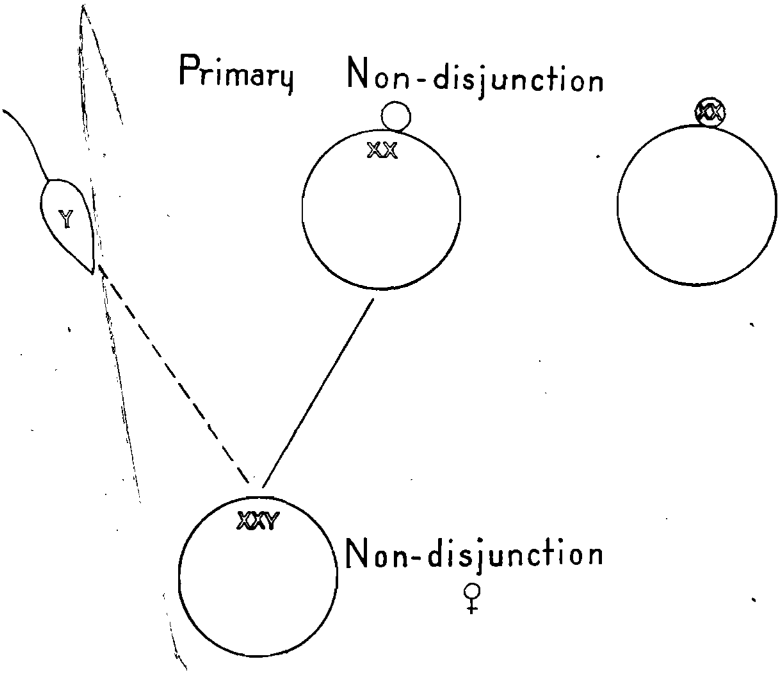


FIG. 34.

Diagram to show the fertilization of an **XX-egg by a Y-sperm,** producing a non-disjunctional **XXY female.**

retained its two X-chromosomes (and one of each of the other chromosomes, Fig. 34) is fertilized by a Y-sperm, an individual is produced—a female—that has two X's and a Y. When the eggs of the XXY female mature, that is, when the reduction of the chromosomes takes place, some irregularity is introduced in the distribution of the

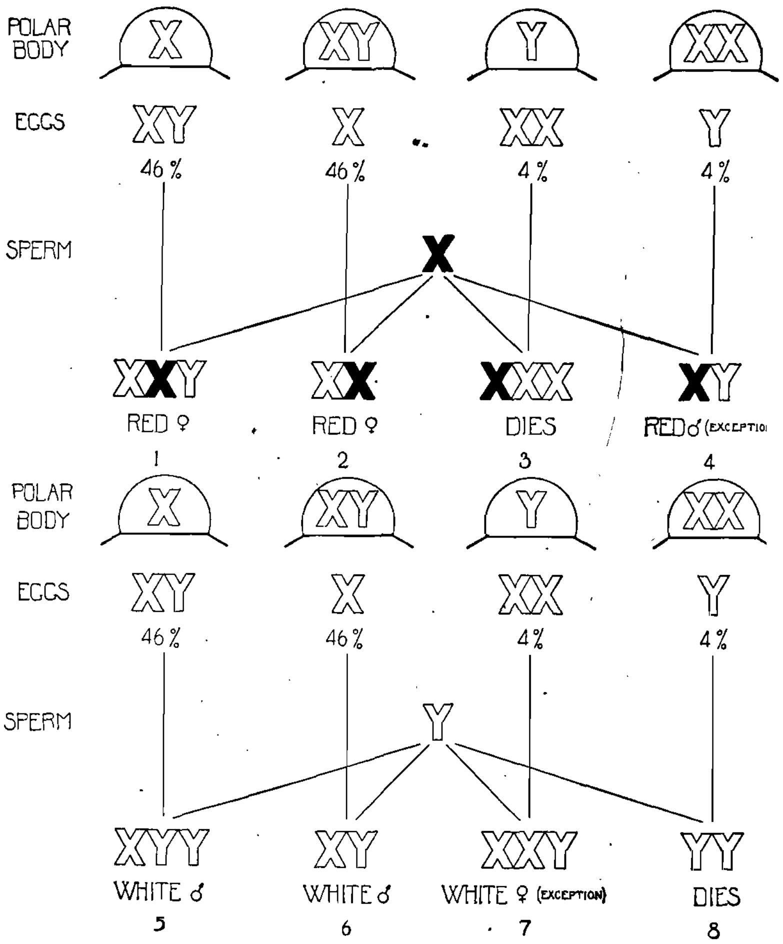


Fig. 35.

Diagram illustrating the fertilization of an XXY-egg, whose X-chromosomes carry each the gene for white eyes, by a red-eyed male. In the upper half of the diagram the fertilization of the four possible kinds of eggs by the red-eyed producing X-chromosome of the male is shown. In the lower part of the diagram the fertilization of the same four kinds of eggs by the Y-chromosome of a male is shown.

two X's and the Y, because the X's may conjugate, leaving the Y free to move to either pole, or one X and the Y may mate, leaving a free X. Possibly all three may come together, and then separate so that two go to one pole of the maturation spindle and one to the opposite pole. The results are practically the same in either case. Four kinds of eggs are expected, as shown in the diagram (Fig. 35).

In order to follow the genetic changes it is necessary that the X-chromosomes of the female or of the male carry one or more recessive genes. For instance, if the two X's in the female carry each the gene for white eyes, and the X in the male carries the allelomorphic gene for red eyes, and if the former are indicated by open (white) X's and the latter by a black X (Fig. 35), the combinations that result are those indicated in the diagram (Fig. 35). Eight kinds of individuals are expected, one of which (YY), not containing even one X-chromosome, is expected to die. In fact, this individual does not appear. Two of these individuals, *viz.*, No. 4 and No. 7, never appear when an ordinary white-eyed (XX) female is fertilized by a red-eyed male. Their presence here, however, is in accord with the expectation from an XXY white-eyed female. They have been tested by genetic evidence and found to correspond to the formula here given them. Furthermore, the white-eyed XXY female has been also shown, by cytological examination, to have two X's and a Y in her cells.

There is one additional kind of female expected that has three X-chromosomes. The diagram indicates that she dies, and this happens in the great majority of cases; but rarely one comes through. She has certain peculiarities by which she can be easily identified. She is sluggish, her wings are short and often irregular (Fig. 36) and she is sterile. A microscopic examination of her cells has shown that she contains three X-chromosomes.

This evidence points to the correctness of the theory

that the sex-linked genes are carried by the X-chromosomes.

There is another aberrant condition in the X-chromosomes that also supports this conclusion. A type of female arose whose genetic behavior could be explained

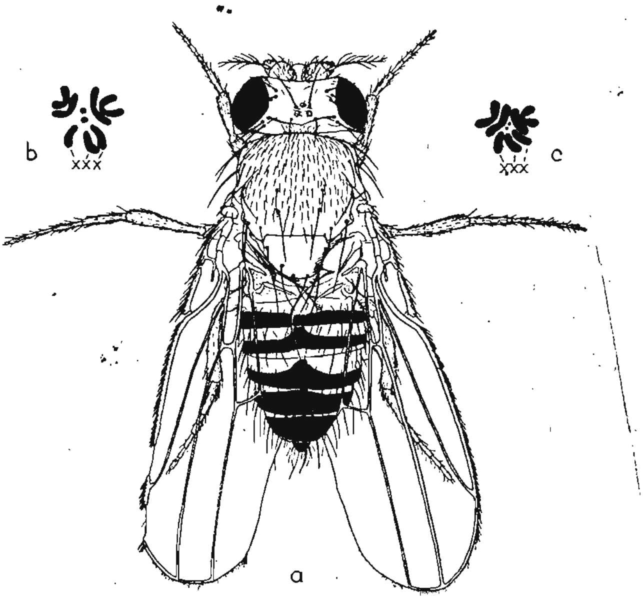


FIG. 36.

A three-X female, a, having three X-chromosomes and two of each of the other kinds (autosomes), as shown in b and c.

only on the assumption that her two X-chromosomes had become attached to each other. During the maturation division of her eggs both X's go together, *i.e.*, they both stay in the egg, or both go out together (Fig. 37). A microscopic examination shows in fact that the two X's of these females are stuck together end to end, and it shows also that these females contain a Y-chromosome that acts, presumably, as a mate of the two attached

chromosomes. The diagram gives the expected results when such a female is fertilized. By good fortune the X-chromosomes that became attached carried each the recessive gene for yellow wings. The presence of the two

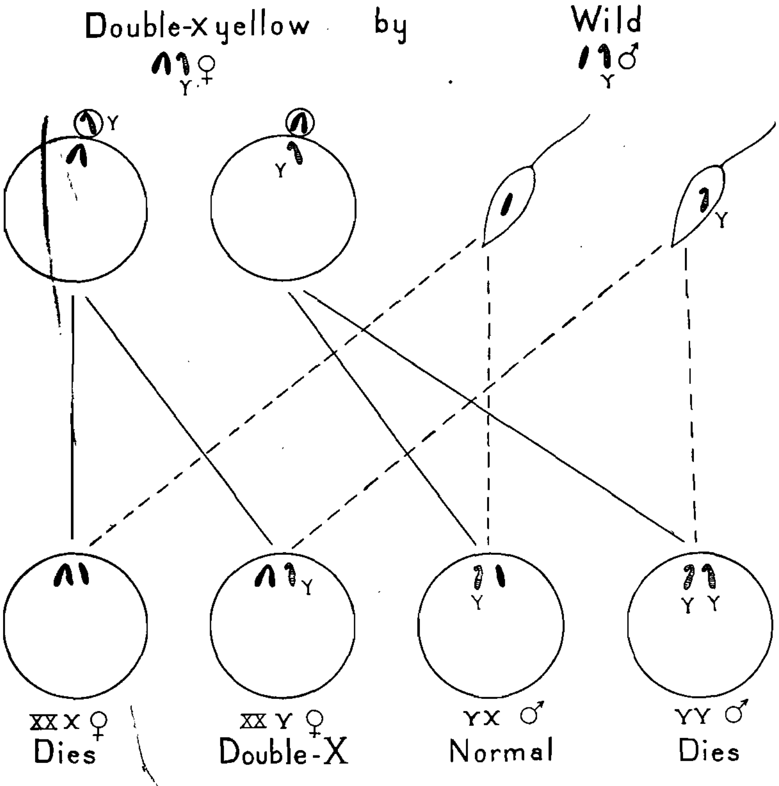


FIG. 37.

Diagram illustrating the fertilization of the two kinds of eggs of an attached, XX, yellow female (whose double X-chromosome is represented here in solid black) by wild type male. There is a Y-chromosome in the double-X female. It is represented here by cross-hatching. The Y-chromosome in the male is indicated in the same way. After reduction two kinds of eggs are present (see above to left). These fertilized by the two kinds of spermatozoa of the normal (wild type) male (see above to right) give the four classes at the bottom of the diagram.

genes for yellow enables us to follow the genetic history of the attached X's when such a female is bred to a normal wild type male with gray wings. For example: the diagram (Fig. 37) shows that two kinds of eggs are expected after the maturation division: one egg retains the double yellow X, the other egg retains the Y-chromosome. If these eggs are fertilized by any kind of male, preferably by one whose X-chromosome contains recessive genes, four kinds of offspring should be produced, two of which die. The two that survive are a double XXY female that is yellow, like her mother, and an XY male that is like his father with respect to his sex-linked characters because he gets his X from his father.

This result is exactly the reverse of what happens when a normal female with recessive genes is fertilized by a different kind of male, and the apparent contradiction is understandable, at once, on the assumption of attached X-chromosomes. A cytological examination of these double X females never fails to show two X's attached to each other.

CHAPTER V

THE ORIGIN OF MUTANT CHARACTERS

THE modern study of heredity has been intimately bound up with the origin of new characters. In fact, the study of Mendelian inheritance is possible only when there are pairs of contrasted characters that can be followed. Mendel found such contrasted characters in the commercial stocks that he used, tall and short, yellow and green, round and wrinkled peas. Later work has also extensively used such material, but some of the best material is supplied by new types whose origin, in pedigree cultures, is better known.

These new characters arise for the most part suddenly, fully equipped, and maintain their constancy in the same way as do the characters in the original type from which they arose. For example, the white-eyed mutant of Drosophila appeared in a culture as a single male. When mated to a common red-eyed female, all the offspring had red eyes (Fig. 38). These were inbred and produced in the next generation red-eyed and white-eyed individuals. All the white-eyed individuals were males.

These white-eyed males were then mated to different red-eyed females of the same generation. Some of the pairs produced equal numbers of white-eyed and red-eyed offspring, both males and females. When the white-eyed individuals were bred together they gave rise to pure white-eyed stock.

We explain these results in accordance with Mendel's first law, which postulates a red-producing and a white-producing element (or gene) in the germinal material.

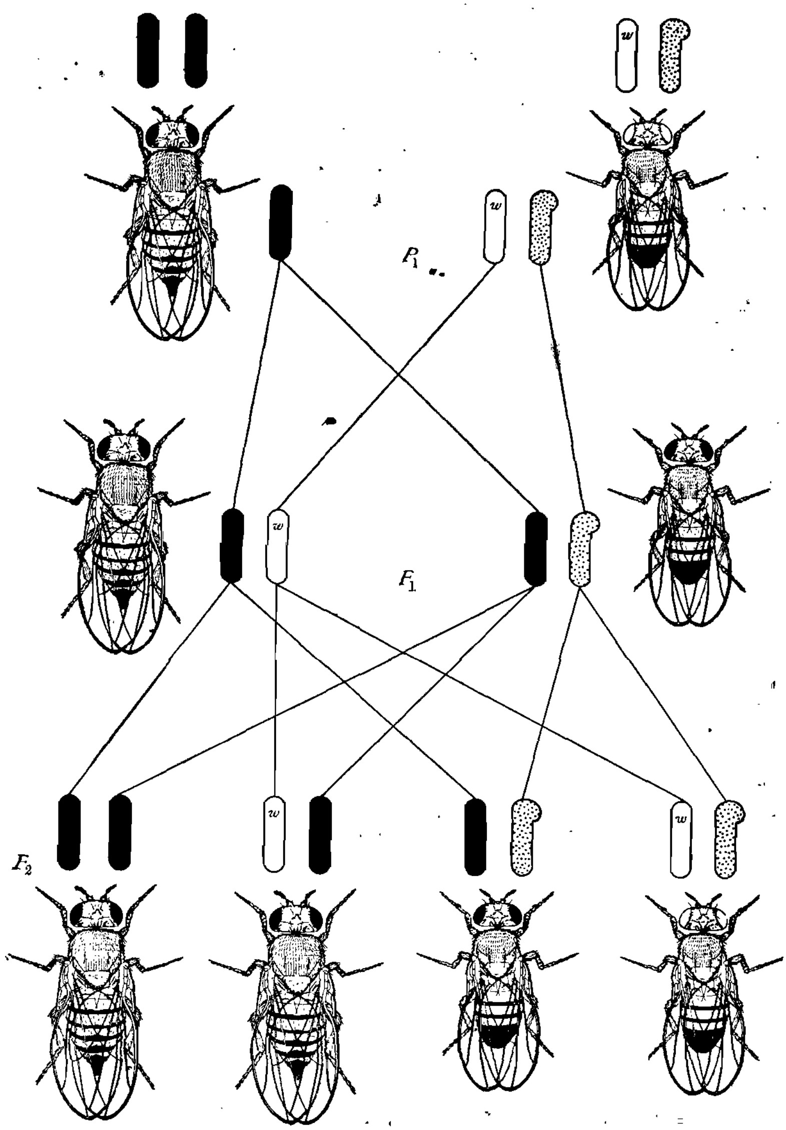


FIG. 38.

Sex-linked inheritance of white eyes in D. melanogaster. A white-eyed male is bred to a red-eyed female. The X-chromosome carrying the gene for red eye is represented by the black rod; the X-chromosome carrying the gene for white eyes is represented by the open rod, and the white recessive gene carried in the chromosome, by small w. The Y-chromosome is stippled.

They behave as a pair of contrasted elements, that are separated in the hybrid at the maturation of the eggs and sperm.

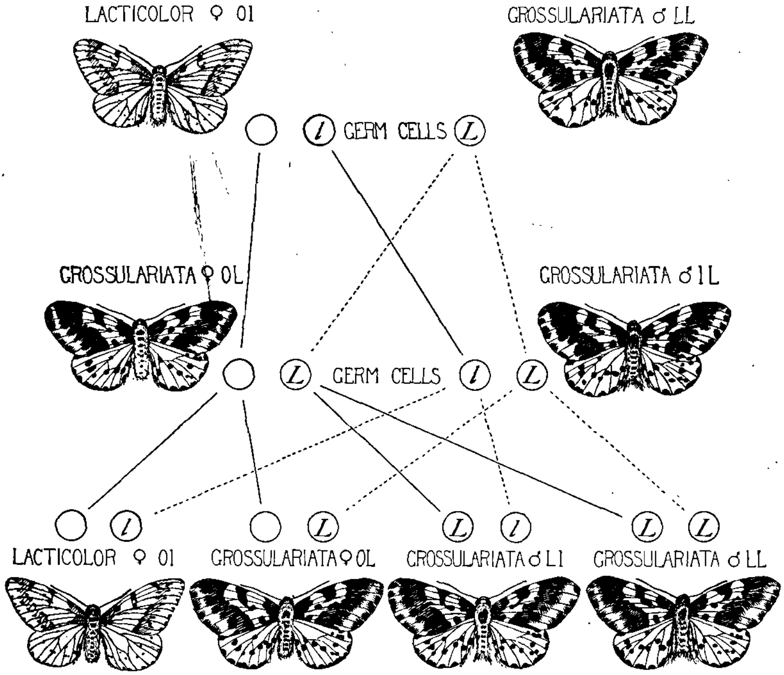


FIG. 39.

Diagram showing a cross between the light-colored type (lacticolor) of Abraxas and the common or dark type (grossulariata). The sex-chromosome carrying the gene for dark color is here indicated by the circle enclosing L, that for light color by the circle with l. The open circle (without an included letter) stands for the W-chromosome that is confined to the females.

It is important to observe that the theory does not state that the white-eyed gene alone produces white eyes. It states, only, that a change took place in some part of the original material, and in consequence of this single change, the material, taken as a whole, now gives rise to

a different end-product. In fact, the change not only affects the eyes, but other parts of the body as well. The sheath of the testes is colorless, while it is greenish in red-eyed flies. The white-eyed flies are more sluggish than their red-eyed fellows, and have a shorter life. It is probable that many parts of the body are affected by the change that took place in some part of the germinal material.

At rare intervals, lighter colored, or pale individuals, of the currant moth, Abraxas, appear in nature. They are females as a rule. A pale, mutant female bred to a dark, wild type male (Fig. 39) gives offspring that are

FIG. 40.

The mutant character Lobe² of D. melanogaster. The eyes are small and protruding.

like the dark type. These, inbred, give the old and the new types as 3 to 1. Pale F_2 individuals are all females. If they are bred to males of the same generation, some pairs give pale males and females, as well as dark types in equal numbers. From the former a pale stock can be reared.

The two preceding mutant characters act as recessives toward the corresponding character in the wild type, but other mutants act as dominants. For example: lobe² is characterized by the peculiar shape and size of the eye (Fig. 40). It arose as a single individual. Half of its off-

spring showed the same character. A change in a gene in one of the second chromosomes must have taken place, either in the mother or father of the mutant. The germ-cell containing this gene met a cell containing a normal gene at the time of fertilization, and the first mutant arose. The first individual was, therefore, hybrid or

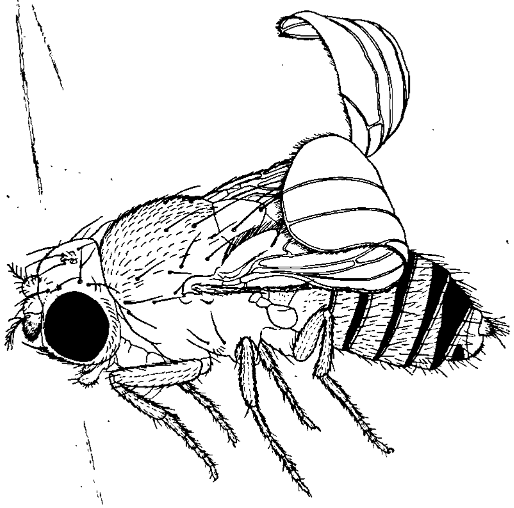


Fig. 41.

The mutant character Curly of D. melanogaster. The wings curl up at the ends and are held somewhat apart.

heterozygous, and, as stated above, produced, when mated to a normal individual, both lobe[2] and normal offspring in equal numbers. From these heterozygous forms some pure lobe[2] flies were produced by mating two lobe[2] individuals. The pure type (homozygous for lobe[2]) resembles the heterozygous type, but the eyes are often smaller, and one or both may be absent.

It is a curious fact that many dominant mutants are lethal in homozygous conditions. Thus curly wing (Fig. 41), a dominant character, nearly always dies when homo-

zygous. Rarely, however, an individual survives. The mutant, yellow coat-color in mice, is lethal as double dominant, as is also the mutant gene for black-eyed white in mice. In all types of this sort, pure breeding stock cannot be produced (except by "balancing" the dominant with another lethal). They produce, in each generation, individuals like themselves and some other type (the normal allelomorph) in equal numbers.

The short-fingered or brachydactyl type in man is a striking dominant character whose inheritance is well known. It will hardly be questioned that it arose as a dominant mutant that established itself in certain families.

All the stocks of Drosophila have arisen as mutants. In the cases that I have given the mutant first appeared as a single individual. In several other cases, however, the new mutant type first appeared in several individuals. In such cases the mutation must have appeared early in the germ-track, so that several eggs or sperm-cells came to carry the mutated element.

At other times a quarter of all the offspring from a pair are mutants. These mutants are recessives, and the evidence shows, in such cases, that the mutation had occurred in an ancestor, and, being a recessive, it did not appear on the surface until two individuals each having the mutated gene met. A quarter of their offspring are then expected to show the recessive character.

Closely inbred stocks are expected to give this sort of result more often than outbred stocks. If outbred, the recessive gene may be distributed to a large number of individuals before two such individuals meet by chance.

It is probable that there are many concealed recessive genes in the human germ-material, since some defective characters recur oftener than expected by independent mutation. When their pedigrees are traced they often

how relatives or ancestors with the same mutant charac-er. Human albinos furnish, perhaps, the best example of is sort. In many cases they come from stocks both of hich carry the recessive gene, but it is always possible iat a new gene for albinos may have been produced by utation. Even then it cannot come to expression until meets another like gene.

Most of our domesticated animals and plants show aracters that behave in inheritance in the same way as the mutants whose origin is established. There can be reasonable doubt that many of the characters have isen by sudden mutations, especially in cases where the omesticated types have come from inbred pedigree ocks.

It is not to be inferred from the preceding examples iat the production of mutants is peculiar to domesticated ces; for this is not the case. There is abundant evi-ence that the same kinds of mutations occur also in ture. Since most of the mutants are weaker or less well-lapted types than the wild type, they disappear before ey are recognized. In cultivation, on the other hand, e individual is protected, and the weaker types have a ance to survive. Moreover, domestic forms, especially ose reared for genetic purposes, are carefully scruti-zed, and our familiarity with them accounts for the tection of many new types.

A study of the occurrence of mutations in the stocks of rosophila has brought to light a curious and unexpected ct. The mutational change takes place in one member ly of a pair of genes—not in both at the same time. is difficult to imagine what kind of an environmental fect could cause one gene in one cell to change, and not e other identical gene. Hence it may seem that the cause the change is internal rather than external. This ques-on will be further discussed later.

TABLE I

RECURRENT MUTATIONS AND ALLELOMORPHIC SERIES

Locus	*Total Occurrences*	*Distinct Mutant Types*	*Locus*	*Total Occurrences*	*Distinct Mutant Types*
apterous	3	1	lethal-a	2	1
ascute	4±	1	lethal-b	2	1
Bar	2	2	lethal-c	2	1
bent	2	2	lethal-e	4	1
bifid	3	1	Lobe	6	3
bithorax	3	2	lozenge	10	5
black	3+	1	maroon	4	1
bobbed	6+	1	miniature	7	1
brown	2	2	Notches	25±	3
broad	6	4	pink	11+	5
cinnabar	4	3	purple	6	2
club	2	2	reduced	2	2
cross-veinless	2	1	rough	2	2
curved	2	2	roughoid	2	2
cut	16+	5+	ruby	6	2
dachs	2	2	rudimentary	14+	5+
dachsoid	2	1	sable	3	2
Delta	2	2	scarlet	2	1
deltex	2	1	scute	4	1
Dichaete	3	3	sepia	4	1
dusky	6+	3	singed	5	3
ebony	10	5	Star	2	1
eyeless	2	2	tan	3	2
fat	2	2	tetraploidy	3	1
forked	9	4	triploidy	15±	1
fringed	2	1	Truncate	8±	5
furrowed	2	2	vermilion	12±	2
fused	2	2	vestigial	6	4
garnet	5	3	white	25±	11
Haplo-IV	35±	1	yellow	15±	2
inflated	2	1			

There is also another fact that a study of the mutation process has brought to our attention. The same mutation may recur again and again. A list of these recurrent mutations of Drosophila is given above. The reappearance of the same mutant indicates that we are dealing with a specific and orderly process. Its recurrence recalls Galton's famous analogy of a polygon. Each change corresponds to a new stable position (here perhaps in a

chemical sense) of the gene. Tempting as is this comparison, we must remember that, as yet, we have almost no evidence as to the real nature of the mutation process.

The mutant types that are most often referred to, or used for genetic material, are as a rule rather extreme modifications or aberrations. This has sometimes given the impression that a mutant change involves a great departure from the original type. Darwin spoke of saltations, which are only extreme mutations, and he rejected them as materials for evolution, because, he said, such great alterations in one part of the body would be likely to throw the organism out of harmony with its environment, to which it is nicely adapted. Today, while we realize fully the truth of this statement, when applied to extreme changes producing malformations or aberrations, we have come, nevertheless, to a realization that minute changes are as characteristic of mutation as are the grosser changes. In fact, it has been shown many times that small changes that make a part a little larger or a little smaller may also be due to genes in the germ-material. Since only the differences that are due to genes are inherited, it seems to follow that evolution must have taken place through changes in the genes. It does not follow, however, that these evolutionary changes are identical with those that we see arising as mutations. It is possible that the genes of wild types have had a different origin. In fact, this view is often implied and sometimes vigorously asserted. It is important, therefore, to find out whether there is any evidence in support of such a view. De Vries' earlier formulation of his famous mutation theory might at first sight seem to suggest the creation of new genes.

The opening sentence of the mutation theory states "that the properties of the organism are made up of units, sharply distinguishable from one another. These

units are bound up in groups, and, in related species, the same units and groups of units recur. Transitions, such as seen in the outer forms of animals and plants, no more exist between the units than between the molecules of the chemist.

"Species are not continuously connected, but arise through sudden changes or steps. Each new unit added to those already present forms a step, and separates the new type as an independent species from the species from which it arises. The new species is '*presto change*,' there. It arises without visible preparation and without transitions."

It may appear from this statement that a mutation that produces a new elementary species is due to the sudden appearance or creation of a new element—a new gene. Put in another way, we witness at mutation the birth of a new gene or at least its activation. The number of active genes in the world has been increased by one.

De Vries has further elaborated his views on mutation in the concluding chapters of *The Mutation Theory* and in his later lectures on "Species and Varieties." He recognizes two processes, one the *addition* of a new element that gives rise to a new species; and the other, the *inactivation* of a gene already present. It is the second view that interests us at present, because, except for the manner of expression, it is essentially the view that is today sometimes said to be the way in which the new types in our cultures arise—through the *loss of a gene*. De Vries himself, in fact, places in this category all the commonly observed cases of loss mutations without respect to their dominance or recessiveness, implying, however, that they are recessive because their gene has become inactive. Mendelian results, he thinks, belong solely to this second category, because of the existence of contrasting pairs of genes—the active one and its inactive mate. These segre-

te, giving the two kinds of gametes peculiar to Men-lian inheritance.

De Vries says that such a process represents a step ckward in evolution. It is not progressive but degres-'e and produces a "retrograde variety." This inter-etation is, as I have said, closely akin to a current :erpretation of mutational changes as due to a loss of a ne—in principle the two ideas are the same.

FIG. 42.
Oenothera Lamarckiana (to the left), and O. gigas (to the right). (After Castle, from Davis.)

[t is not without interest, therefore, to examine the idence that led de Vries to develop his mutation hy-thesis.

De Vries found near Amsterdam, in a waste field, a ony of evening primroses, *Oenothera Lamarckiana* ig. 42). Amongst them were a few individuals that dif-'ed somewhat from the common forms. He brought ne of these into his garden and found that they bred ie for the most part. He also bred the parent form, or *marckiana*. It produced, in each generation, a small mber of the same new types. In all, about nine such

types were recognized at that time. These were the new mutants.

Now it has turned out that one of these types is due to doubling the number of the chromosomes. It is called gigas (Fig. 42). One is a triploid, semigigas. Several of the types are due to the presence of an extra chromosome. These are called *lata* and *semilata* forms. One at least, brevistylis, is a point-mutant, like the recessive mutants of Drosophila. It is, then, to *O. brevistylis,* and to the residue of recessive mutants, that de Vries must appeal.[1] It appears, now, highly probable that this residue (the recessive mutants) conform to the Drosophila mutant types, but their manner of reappearance in nearly every generation gives a picture entirely different from that of mutation in Drosophila and other animals and plants. A possible interpretation may be found in the presence of lethal genes closely linked with these recessive mutant genes. Only when the recessive gene is released from its near-by lethal through crossing-over is there an opportunity for it to come to expression. It has been possible in Drosophila to make up balanced lethal stocks carrying recessive genes that simulate closely Oenothera. Only when crossing-over occurs does the recessive reappear. The frequency of its appearance is dependent on the closeness of the lethal to the recessive gene.

It has been found that other species of wild Oenotheras behave in the same way as Lamarck's evening primrose, whose peculiarities in inheritance are, therefore, not due to a hybrid origin (as has been sometimes surmised), but due, in the main, to the presence of recessive genes linked to lethal factors. The appearance of the mutant types does not represent the mutation process that pro-

[1] De Vries and Stomps both thought that some of the peculiarities of O. gigas are due to other factors than chromosome number.

uced the mutant gene but rather its release from its ethal linkage.[2]

It seems, then, that the mutation process in Lamarck's rimrose is probably not essentially different from familiar processes that occur in other plants and animals. In other words, there are no longer grounds for interpreting the mutation process that it shows as differing essentially from what takes place in other animals and plants, except that some of its recessive mutant genes are concealed, owing to the presence of lethal genes.

These considerations remove, I think, any necessity for assuming that a new gene is added, even when a new or progressive type of Oenothera appears. It may be that such progressive types as de Vries had in mind arise through the accidental addition of a whole chromosome to the normal set. This question will be considered in Chapter XII, but it may be said here that there is very little evidence that new species can often be produced in this way.

[2] Shull has interpreted the appearance of a number of the recessive types of *O. Lamarckiana* on the lethal-linkage hypothesis. S. H. Emerson has recently pointed out that Shull's evidence, so far published, is not entirely cogent, but it may, nevertheless, be valid. De Vries himself, in recent publications, seems not averse to accepting the lethal interpretation for certain of the oft-repeated recessive mutants that he places in the "central chromosome."

CHAPTER VI

ARE MUTANT RECESSIVE GENES PRODUCED BY LOSSES OF GENES?

MENDEL did not consider the question of the origin or the nature of the genes. He represented in his formula the dominant gene by a capital letter and the recessive gene by a small letter. The pure dominant was AA and the recessive was aa and the hybrid, or F_1, was Aa. The question as to origin did not arise, because the characters yellow and green, tall and short, round and wrinkled, were already present in the peas selected for the experiment. Only later, when the relation of the *mutants* to the *wild* species from which they were supposed to have come was considered, did their origin arouse interest. A specific case, that of rose comb and pea comb in domestic fowls, seems to have had something to do with the reasoning that led to an interpretation of recessive genes as losses or absences.

Certain breeds of domestic poultry have a comb called rose (Fig. 43c). They breed true to this type of comb. Other races have a comb called pea (Fig. 43b). They also breed true to their type. If these breeds are crossed, the F_1 has a new form of comb, called walnut (Fig. 43d). If two F_1 fowls with walnut combs are mated, the offspring show 9 walnut, 3 rose, 3 pea, to 1 single. The numerical result shows that two pairs of genes are involved, rose and not-rose, pea and not-pea. The single comb is not-rose, not-pea, which was then interpreted to mean the absence of pea and of rose genes. But the not-presence of pea and not-presence of rose genes does not prove

necessarily that the allelomorphs of these genes are absences. The allelomorphs may be only other genes that do not give rise either to pea or to rose comb.

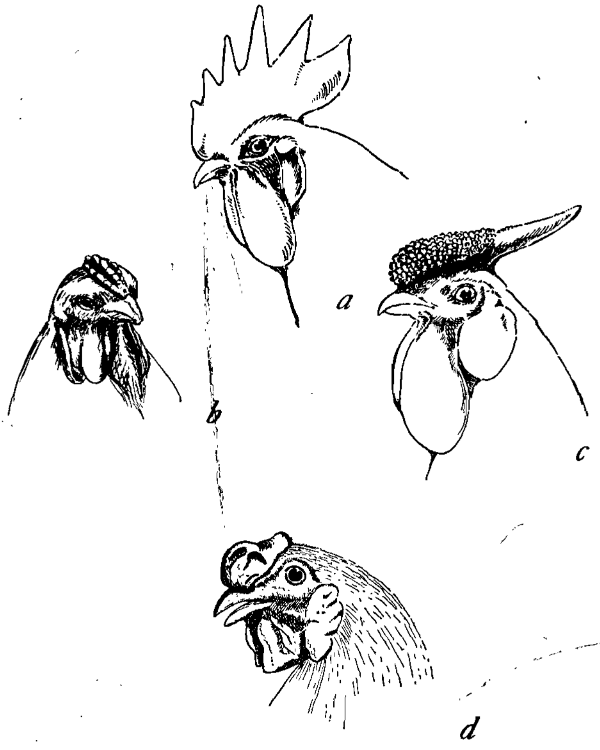


FIG. 43.

Combs of domesticated races of fowls. a, single comb; b, pea comb; c, rose comb; d, walnut comb (the hybrid or F_1 type when pea and rose are crossed).

The result may be stated in another way that may make ıe situation more obvious. If we assume that the wild ıngle fowl, from which our domesticated races have ɔme, had a single comb, and that at some time a domiant mutation occurred that gave a pea comb, and at

another time, in another bird, a dominant mutation occurred that gave a rose comb, it follows that in the cross described above, the F_2 single comb is due to the presence of the original wild type genes. Thus, a race with pea comb (PP) will contain the wild type genes (rr), from which the rose comb arose by mutation. Similarly the race with rose comb (RR) will contain the wild type genes (pp), from which the pea comb arose by mutation. The formula for the pea comb race is then PPrr and for the rose comb race RRpp. The germ cells of these two races will be Pr and Rp respectively, and the F_1 will be PpRr. The two dominants produce a new type, the walnut comb. Since two pairs of genes are present in F_1 there will be 16 combinations in F_2, and of these one will be pprr or single comb. The single comb is due then to the recombination of the wild type recessive genes that entered the cross.

Recessive Characters and Absences of Genes.

In the background of the presence and absence theory there lurks, beyond doubt, the idea that many recessive characters are actual losses of some character that was once present in the original type, hence by implication the gene of that character is also absent. This idea is a hang-over of Weismann's theory of the relation of determinant to character.

It is instructive to look a little closer into the evidence that may have seemed at first to support such an interpretation.

An albino rabbit or rat or guinea pig may be interpreted to have lost the pigment characteristic of the original type. In a sense no one will deny that the relation of the two types may be expressed in this way, but, in passing, it may be noted that many albino guinea pigs have a few colored hairs on the feet or toes. If the pigment-pro-

ducing gene is absent and if color depends on the presence of this gene it is difficult to explain the presence of these colored hairs.

A mutant race of Drosophila is called vestigial (Fig. 10) because only vestiges of the wings are present, but if the larvae are reared at a temperature of about 31°C. the rudiments are quite long and in extreme cases may be almost as long as the wings of the wild type. If the gene for producing long wings is absent, how can a high temperature bring it back again?

There is another highly selected race of Drosophila in which the eyes are absent in most individuals, but small eyes may be present in other individuals (Fig. 30). As the culture gets older more and more of the flies have eyes and the average size of the eyes is larger. It is not probable that the gene changes as the culture gets older and if it were absent in the eyeless flies that first hatch, it is not likely that the age of the culture could bring back the missing gene. Moreover, if this were the case, flies from the older culture should produce offspring more of which had eyes or larger eyes than the average of the race, but this does not happen.

In still other recessive mutant types the loss of the character itself is by no means obvious. A black rabbit is recessive to the gray wild type. The black rabbit has actually more pigment than has the gray rabbit.

There are dominant genes that produce pure white individuals. The white leghorn race of fowls is due to such a factor. Here the argument is reversed, and it is said that there is present in the wild type jungle fowl a gene that suppresses white plumage. When this suppressing gene is lost the bird is then able to develop white plumage. Logical as this argument may appear, the assumption of the presence of factors of this sort in the wild bird seems far fetched, and in the light of the occur-

rence of other dominant characters, the argument is not one that makes a favorable appeal but seems rather a forced attempt to save the theory at all costs.

It must be remembered, too, that the distinction between recessive and dominant genes is largely arbitrary. Experience has shown that characters are by no means always recessive or dominant. On the contrary, in a large majority of cases, a character is not completely dominant or completely recessive. In other words, the hybrid type, containing a dominant and a recessive gene, lies somewhere between the parent types—both genes have some effect on the character produced. When this relation is realized, the theory that a recessive gene is an absence does not appear in so favorable a light. It is true that it might be claimed in such cases, with some grounds for justification, perhaps, that the hybrid is intermediate because one dominant gene produces less effect than two dominant genes, but this introduces a new feature into the situation. It does not necessarily mean that the effect is really due to one absence. It can be brought into line with this assumption perhaps, but is not a necessary inference.

If the preceding arguments are admitted as cogent we might dismiss this interpretation of the meaning of the recessive gene taken in a literal sense. But in recent years another interpretation of the relation between the effect of all the genes and the character has appeared that makes the refutation of the presence and absence view much more difficult. For example, suppose a gene were actually lost from a chromosome and that when two such chromosomes are brought together, some character of the individual is modified or even absent. The modification or absence might be said to be the effect produced by all the rest of the genes. It is, not the absence, as such, that determines the result, but the effect produced, when two

ɜnes are absent, by the rest of the genes. Such an inter-:etation avoids the rather naïve assumption that each ɜne in itself represents a character of the individual.

Before discussing this view it should be pointed out :at in certain aspects this interpretation is similar to, ıd in fact derived from, another more familiar interpre-.tion of the relation between gene and character. For ɜtance, if the mutation process is interpreted to mean change in the constitution of a gene, the result that llows, when two recessive mutant genes are present, not that the new character is due to the new gene alone, t that the new character is the end product of the tivity of all the genes, including the new ones, in the me sense that the original character was also due to e original gene (that mutated) and to the rest of the nes.

These last two interpretations may be briefly stated follows: The first one states that in the absence of a ir of genes all the rest of the genes are responsible for e mutant character. The second states that when a gene anges its constitution, the end-result, produced by the w genes, and the rest of the genes, is the mutant aracter.

There is a certain amount of recently obtained evidence at has some bearing on the question here at issue ;hough it cannot be said to furnish a decisive answer favor of either view. The evidence is, nevertheless, ›rth considering on its own merits, since it brings out rtain possibilities relating to mutation that have not, far, been discussed.

There are several mutant stocks called collectively tch that can be identified by one or more incisions at e end of the wings and by the thickening of the third in of the wing (Fig. 44). Only females having these aracteristics appear. Any male carrying the gene for

notch dies. The factor is carried in the X-chromosome. The notch female has one X carrying the factor for notch and another X with its normal allelomorph (Fig. 45). Half of her ripe eggs retain one X, half the other. If she

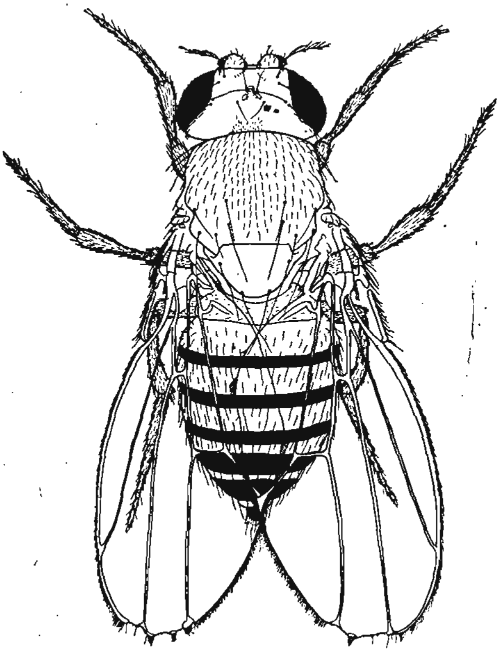


FIG. 44.
Notch-wing, a dominant sex-linked, recessive lethal of Drosophila melanogaster.

is fertilized by a normal male, an X-sperm uniting with an egg carrying the normal X produces a normal daughter; an X-sperm uniting with an egg carrying the notch-bearing X produces a notch daughter. A Y-sperm uniting with an egg carrying a normal X produces a normal son; a Y-sperm uniting with an egg carrying a notch-bearing X forms a combination that dies. The output is two daughters to one son.

As far as this evidence goes, notch might be interpreted as a recessive lethal gene that acts as a dominant wing modifier in the hybrid. It was later shown by Metz and Bridges (1917) and by Mohr (1923) that more of the X-chromosome is involved in the notch mutation than in

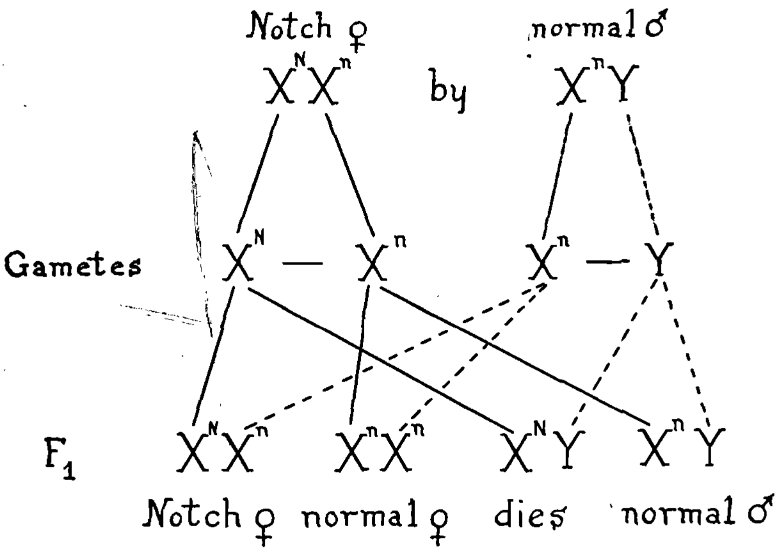


FIG. 45.

Diagram to illustrate a cross of a Notch female, $X^N X^n$ by a normal male, $X^n Y$. The X-chromosome with Notch is X^N; the other X, carries the normal allelomorph, X^n.

an ordinary "point mutation"; for when *recessive* genes are present in the region of notch in one X-chromosome, and notch in the other X-chromosome, the recessive characters appear in such an individual as though a certain region of the notch chromosome were absent or at any rate inactive (Fig. 46a). The result is practically the same as though an absence had actually arisen. In some of the notch mutants the "lost" region extends over about 3.8 units (from the left of white to the right of

abnormal) (see chart, Fig. 19); but in other notches the lost region extends over fewer units. In each case the test seems to mean that a small piece (more or less) of the chromosome has, in some sense, dropped out.

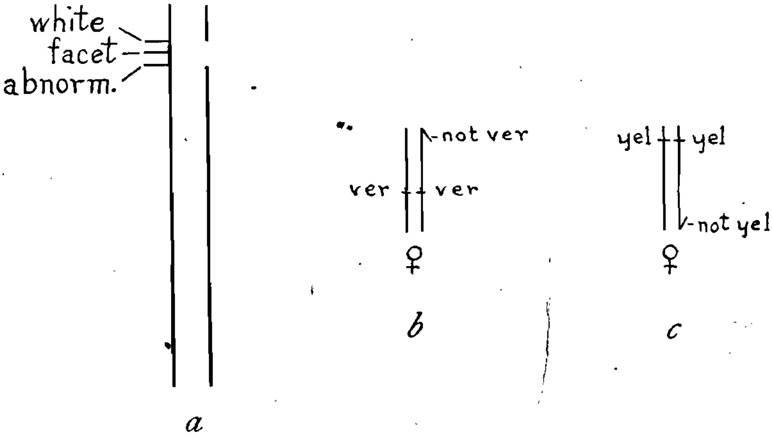


FIG. 46.

Diagram a, showing the location of the genes in the Notch-bearing chromosome. In the right-hand rod the break in the chromosome stands for Notch. In the left-hand rod the location of three recessive genes (white, facet, abnormal), that stand opposite Notch, are indicated. In b the translocation of a piece of an X-chromosome to another X is shown. There are two vermilion-bearing X-chromosomes to one of which the piece is attached carrying the normal allelomorph of vermilion, *i.e.*, not-vermilion. In c there are two yellow-bearing X-chromosomes to one of which is attached a piece carrying the normal allelomorph of yellow, *i.e.*, not-yellow.

As has been stated, recessive genes, when opposite t notch, produce their recessive characters. This is con sistent either with the view that these recessives ar absences and the effect is produced by all the rest of th genes, or with the view that the recessive genes are pres ent and produce their effect in combination with all th rest of the genes. The result does not permit a decisio between the two views.

'here is, nevertheless, a slight difference between the racter produced by two recessive genes in this region l one recessive and the notch "absence." This differe might seem to be due to one real absence (notch) and recessive not being equivalent to two recessive genes, further consideration shows that the two situations not quite comparable owing to the absence of other es in the lost notch piece. These genes are present in double recessive type, and the slight differences in the ult in the two cases may be referable to the presence absence of these other genes.

n the preceding case it has not been possible to show cytological evidence that a piece of the X-chromosome absent in the notch mutant—its absence is deduced m the genetic evidence alone. In the next case, howr, an actual absence has been demonstrated.

)ccasionally one of the small fourth chromosomes is ; (haplo-IV, Fig. 29). This chromosome carries, in tain mutant stocks, recessive genes. It is possible to ke up an individual that has a recessive gene—eyeless r example—in its single IV-chromosome. Such individls show the characteristics of the eyeless stock but are, a class, more extreme than when two eyeless genes are esent. This difference may be due to the absence of the ier genes in the absent chromosome.

A different relation arises in the case of translocation, called by Bridges and Morgan (1923) which means it a piece of a chromosome has become detached and reached to some other chromosome. It perpetuates itself, d, owing to the genes that it carries, introduces a comcation into the genetic results. For example, a piece the normal X-chromosome in the region of the verlion locus became attached to another X-chromosome ig. 46b). A female with vermilion genes in each of its chromosomes and the transposed piece attached to one

of them (Fig. 46b) is vermilion despite the fact that one normal allelomorph of vermilion is present in the piece. At first sight it may seem, if the vermilion genes are interpreted as absences, that two absences cannot possibly dominate one presence. On second thought, however, another explanation is possible, for, if the vermilion eye color is due to the action of all the other genes when vermilion is absent, the same result might happen even though one dominant normal allelomorph is present. The situation is not identical with one in which a vermilion gene is present in one chromosome and its normal allelomorph in the other.

The relation shown here between two recessive genes and a dominant gene in the translocated piece does not always lead to the development of the recessive character. For example, there is another case of translocation reported by L. V. Morgan. A piece of an X-chromosome of the region of the mutant genes yellow and scute became stuck to the right end of an X-chromosome. A female that has the recessive genes for yellow or for scute in each of her X-chromosomes (Fig. 46c) and a piece attached to one of these X's shows the wild type character. Here the effects of the recessive genes are counterbalanced by the dominant allelomorphs of the attached piece. This is interpreted to mean that all the other genes, plus those in the attached piece, combine to turn the scale toward the dominant type and this is expected on either of the contrasted interpretations as to the nature of the gene.

The relation of two recessive genes to one dominant has also been studied in the triploid endosperm of corn and in one triploid animal. The nuclei of the endosperm cells of the seed of corn arise from the union of one pollen grain (haploid in chromosome number) and two nuclei of the embryo sac (each haploid). A triploid or threefold

nucleus results (Fig. 47), which by division gives rise to the triploid nuclei of the endosperm cells. In floury corn the endosperm is composed of soft starch, while flint corn has a large amount of corneous starch in the endosperm. If a floury corn be used as the female parent (ovule) and

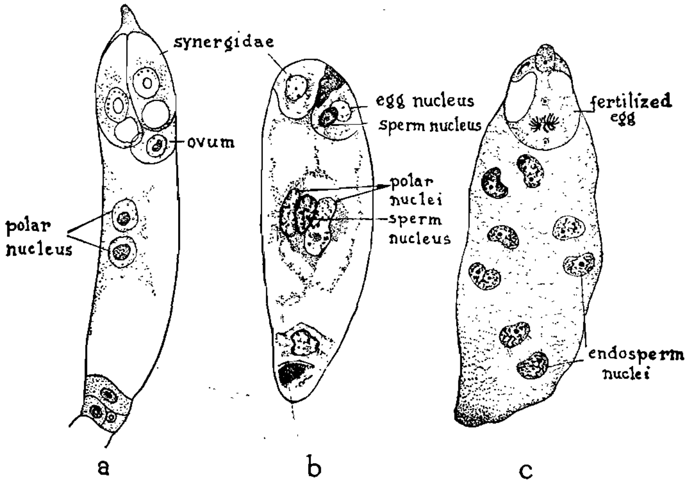


FIG. 47.

Three stages in the fertilization of the egg-nucleus in the embryo sac of plants. In b the two maternal haploid nuclei and the single paternal haploid sperm nucleus are shown. By their union the triploid endosperm is produced as shown in c. (After Strasburger and Guinard from Wilson.)

inty corn as the male parent (pollen) the seeds pro-uced by the F_1 plant have floury endosperm. The result shows that two floury genes are dominant over one flinty gene (Fig. 48a). If the reciprocal combination is made, flinty female parent and floury pollen, the F_1 seeds are flinty (Fig. 48b). Here two flinty genes dominate one floury. It is a matter of choice which gene is chosen to represent the absence of the other. If the absence is floury, then two absences would be said to dominate one presence

in the first case, and two presences to dominate one absence in the second case.

The interpretation of two absences dominating a presence would have no meaning if taken literally, but as has been pointed out it is possible to explain such a statement, if, in the absence of a gene, the floury character is determined by the rest of the genes, and, of course, the same

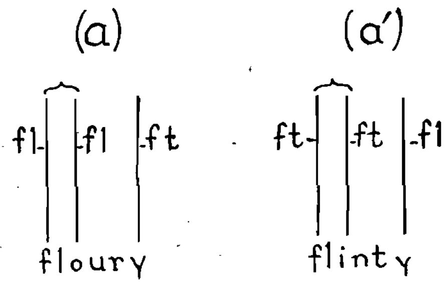


FIG. 48.

Diagrams of triploid condition of endosperm of corn when, as in a, two floury genes and one flinty are present giving floury endosperm; and when, as in a′, two flinty genes and one floury gene are present giving flinty endosperm.

explanation applies if there is present a gene for floury (a mutated gene from flinty) whose effect is produced by itself plus the rest of the genes. This evidence from triploid endosperm is no more decisive than when a translocated piece of a chromosome introduces a third element into the situation.

There are several other cases in corn where two recessive elements do *not* dominate a single dominant, but these have no further bearing on the present question.

If a triploid female Drosophila has a vermilion gene in each of two of its X-chromosomes and a red gene in the third, the resulting eye color is red. One dominant gene here dominates two recessives. This result is the opposite

of that where the wild type (dominant) gene present in the duplicated piece was opposed to two vermilion genes. The two situations are, however, not identical in all respects, for the triploid differs from duplication by the occurrence of nearly an entire X-chromosome instead of only a short piece of this chromosome. The excess of genes in the extra X-chromosome may account for the difference in the two cases and this holds equally whether the recessive genes be interpreted as real absences or as mutated genes.

The Bearing of Reverse Mutation (Atavism) on the Interpretation of the Mutation Process.

If recessive genes arise by losses, then there is little expectation that a pure recessive stock would ever produce again the original gene, since this would mean apparently the production of something highly specific from nothing. On the other hand, if mutation is due to a change in the constitution of the gene, it seems less difficult to imagine that the mutated gene might sometimes return to the original condition. It may be that we know too little about the gene to give much weight to such arguments; nevertheless, the occurrence of return mutants would appear more plausibly explained on the latter view. Unfortunately the evidence bearing on the question is not entirely satisfactory. There are, it is true, a number of instances in Drosophila where a mutant recessive stock has given rise to an individual with the original or wild type character; but an occurrence of this sort, unless controlled, cannot be accepted as sufficient evidence, since the chance of contamination of the stock by a wild type individual is not to be ignored. If, however, a mutant stock is marked by several mutant characters, one only of which reverts, the occurrence furnishes the desired evidence, provided no other combinations of these mu-

tants are present in the vicinity at the time. There are a few recorded cases in our stocks that fulfill these conditions, and the evidence, as far as it goes, shows that reversal may take place. There is also another possibility that has to be guarded against. Some of the mutant stocks have, after a time, seemed to lose more or less the characteristics of that stock, yet when outbred it has been found that the mutant character can be recovered in its original strength. The fourth chromosome character, bent wings (Fig. 30), that is itself variable, and subject to environmental influence, has shown, when not selected, a tendency to return to the wild type in appearance. If a fly of this kind is outcrossed to wild stock and the F_1's inbred, the bent character reappears in many of the individuals of the expected bent class. A similar result has been found in another mutant stock called scute, characterized by the *absence* of certain bristles on the thorax. Individuals appeared in certain pure cultures in which the "missing" bristles were present. Apparently the mutant had reverted to wild type. But that this had not occurred was shown by breeding such flies to wild type stock. In the second generation, scute flies reappeared. A study of this case has shown that the return to normal was due to the appearance of a recessive factor which, when present in homozygous condition in scute stock, brings about the development there of the missing bristles. Aside from the bearing of this result on the question under discussion, the fact of a new recessive mutation occurring, that brings back the mutant character to the original type, is in itself an interesting and important fact.

Finally, there is the peculiar reversion to normal of the dominant or semi-dominant character, bar-eye (Fig. 49, 1 and 2). For some years it has been known from the observations of May and Zeleny that bar-eye reverts

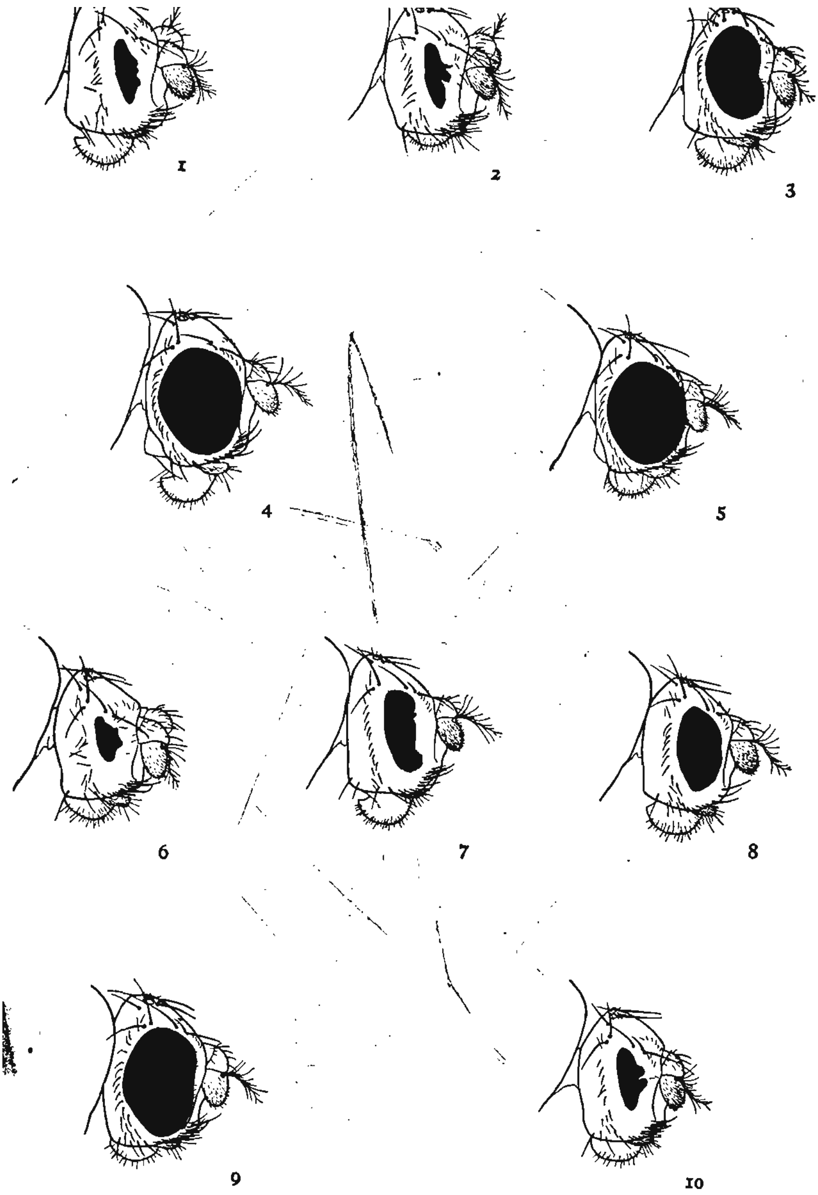


FIG. 49.

Different types of bar eyes; 1, homozygous bar female; 2, bar male; 3, bar-over-round eye female; 4, female homozygous for round that was obtained by reversion; 5, male that carries the gene for round eye obtained by reversion; 6, double-bar male: 7, *homozygous infra-bar female*; 8, *infra-bar male*; 9, *infra-bar-over-round female*; 10, double-infra-bar male.

to normal eye, and this instance has been cited as evidence that reverse mutation may take place. The frequency of the return mutation varies in different stocks. It has been estimated to occur about once in 1600 times. It was later discovered by Sturtevant and Morgan that when the reversion occurs, crossing-over takes place in the vicinity of the bar gene, and Sturtevant has obtained crucial evidence in regard to the nature of the changes that there take place.

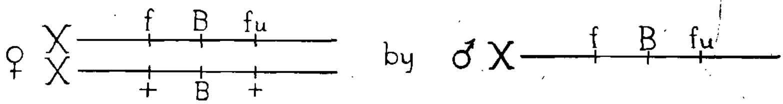


FIG. 50.

Diagram of a cross between a female bar-eyed fly, heterozygous in forked and fused, and a forked bar fused male.

The demonstration that crossing-over takes place whenever reversion occurs, was as follows: To the left and very close to bar (⅕ unit) there is a gene called forked; to the right and very near bar (2½ units) a gene called fused. A female is made up with bar lying between these two genes in one X-chromosome, and bar with the wild type allelomorphs of forked and fused in the other (Fig. 50). Such a female is bred to a forked bar fused male. The ordinary sons will be either forked bar fused or bar, since each has received either the forked bar fused or the not-forked bar not-fused X-chromosome of the mother. When, as happens rarely, a reversion takes place, *i.e.*, a male appears that has round eyes, it is observed that crossing-over has taken place between forked and fused. For example, the reverted male is either fused or else forked; it is never forked and fused, nor is it ever both not-forked and not-fused. Crossing-over must have

taken place in the mother of the male between forked and fused. The total cross-overs between forked and fused are less than 3 per cent and yet they include all the reversions to full eye.

Only the reverted sons have been spoken of above in order to simplify the situation, but of course the reverted chromosome might have passed into an egg that develops into a female. The experiment can be so planned that evidence of crossing-over will also be detected in the reverted daughter. The ordinary daughters will be homozygous bar (see Fig. 49, 1). The reverted daughters will be heterozygous for bar eyes, and either forked or fused. None of them are both forked and fused and none of them are not-forked not-fused.

The crossing-over, that brings about reversion to round eye, must not only have left one X-chromosome without a bar gene, but must have put the other bar gene into the bar chromosome (Fig. 51a). In appearance a male with two bar genes (double bar) is similar to a male with one bar gene, but its eyes are smaller and the number of its facets is reduced. It has been named double bar (Fig. 49, 6). The presence of two allelomorphic genes in the same linear series is an exceptional occurrence that has as yet not been observed in any other mutation. It can be pictured only by supposing that the bar genes lying opposite to each other before crossing-over are shifted a little when the crossing-over occurs. The result is that the double bar chromosome is lengthened by one bar gene at least, and conversely that the other chromosome has been shortened by the "loss" of the bar gene.

Sturtevant has put the theory of reversion of bar to a number of critical tests. There is an allelomorph of bar (that arose as a mutation of bar) called infra-bar (Fig. 49, 7 and 8), whose eyes are somewhat different in size

and in the number of facets. In infra-bar stock, reversion also takes place (Fig. 51b), producing a full round eye closely similar to wild type, and a new type called double-infra-bar (Fig. 49, 10).

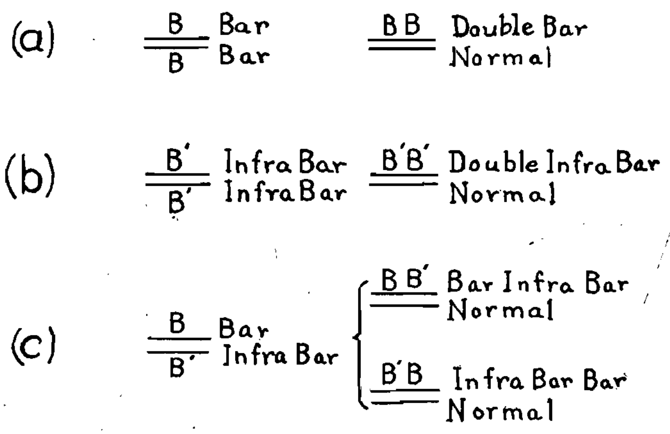


FIG. 51.
Diagram of mutation in bar and infra-bar and bar-infra-bar.

A female with bar in one chromosome and infra-bar in the other (Fig. 51c) produces, when reversion takes place, a full round eye (wild type) and bar-infra-bar or infra-bar-bar types (Fig. 51c).

Sturtevant has also utilized these two types, the bar-infra-bar type and the infra-bar-bar, in order to prove that when crossing-over takes place in bar-infra-bar over normal (Fig. 52a), the result gives either forked bar or else infra-bar fused, and when crossing-over takes place in infra-bar-bar over normal (Fig. 52b) the result is either forked infra-bar or bar fused, provided the mutant genes all lie in the same chromosome, as shown in the diagram (Fig. 52a, b).

It follows that in both types the genes not only keep their identity but also their sequence. From the way in which the two types, fBB′fu and fB′Bfu, were made up, the sequence of the genes is known, and in all cases the breaking apart of B and B′ agrees with the sequence previously determined.

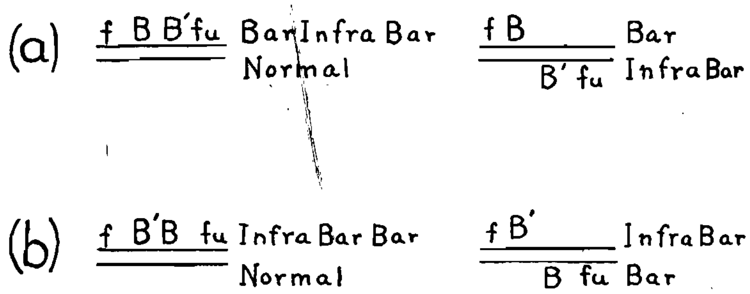


FIG. 52.

Diagram, in a, of a mutation of forked bar, infra-bar fused and in b, a mutation of forked infra-bar, bar fused.

These results furnish crucial evidence in favor of the correctness of the theory that reversion in bar is due to crossing-over. This is, at present, a unique case. There would seem to be some peculiarity in the X-chromosome at the bar locus that allows crossing-over between allelomorphic factors to occur. Sturtevant speaks of this as unequal crossing-over.[1]

This result raises the question as to whether all mutations may not be due to crossing-over. There is explicit evidence in Drosophila that this is not the general expla-

[1] Several curious problems concerning the bar locus are involved in these relations. For instance, when bar crosses over what is left in the bar locus? Is it an absence of bar? Did the original bar arise by mutation in a wild type gene, or was a new gene created? These questions are still under investigation.

nation of mutations, because, for one reason, it is well known that mutation may occur in the male of Drosophila as well as in the female. In the male of Drosophila there is no crossing-over.

The Evidence from Multiple Allelomorphs.

It has been shown in Drosophila, as well as in a few other types (in corn, for example), that more than a single mutation may occur at the same locus. The series of allelomorphs at the locus for white eye in Drosophila is the clearest case of the sort. No less than eleven eye colors, in addition to the red eye of the wild fly, have been recorded. They form a graded series from white to red as follows: white, écru, tinged, buff, ivory, eosin, apricot, cherry, blood, coral, wine. They have not, however, appeared in this sequence, although white was the first mutation observed at this locus. That they have not arisen by the mutation of a series of adjacent genes is clearly shown by their origin and their relation to each other. For example, if the white were due to a mutation from the wild type at one locus and cherry by mutation at an adjacent locus, then when white is crossed to cherry the female offspring should have red eyes, because white would, on this assumption, carry the wild type allelomorph of cherry and cherry would carry that of white. When white and cherry are crossed they do not give this result, but the daughters have an intermediate eye color. The F_1 female gives again white and cherry sons in equal numbers. The same relation holds for all the other allelomorphs, any two of which can exist simultaneously in any one female.

If the presence and absence theory is taken literally there cannot be more than one absence for each gene. The theory in this form is disproven in all cases where the occurrence of multiple allelomorphs is known to have

ken place independently from the wild type;[2] but it is ssible to interpret absence in such a way that it is not contradiction with the occurrence of multiple allelo- orphs. Suppose, for instance, that different quantities of materials are lost at the locus in question for each mutant type. The loss of one quantity might stand for white, another quantity for cherry, and so on. The result might then not appear to be inconsistent with the facts, although it should be noted that the assumption calls for a somewhat different interpretation of the gene as a unit. The "compound" formed by the presence of two of these allelomorphs might then not be expected to give the wild type but something else. To admit this, however, changes the idea of presence and absence in such a way as to make it essentially the same as the view that is here maintained, namely, that mutation is due to a change of some sort in a gene. There is no advantage, that I can see, in urging that the change must be a loss of part of the gene (gene meaning a quantity of something at a given locus). This is a gratuitous assumption in regard to the nature of the change—one that is not necessary to explain the results. It may be, of course, that a gene may be lost or a part of a gene may be lost and a new mutant result, but it is theoretically possible that the constitution of the gene may change in some other way. So long as we do not know anything definite concerning the kind of change that takes place there is nothing to be gained by limiting it to only one kind of process.

[2] If the multiple allelomorphs had arisen seriatim, *i.e.*, one from another, then of course it might be possible that each one carried the preceding mutant gene. If so the two when crossed would not give the wild type. But when, as in Drosophila, each has arisen independently from the wild type the situation is different, as explained in the text.

Conclusions.

An analysis of the evidence at hand does not justify the view that the actual loss of some character present in the original type must be interpreted to mean that a corresponding loss has taken place in the germinal material.

Even by extending the literal interpretation of the presence and absence idea so that the postulated connection between the loss of the character and the loss of the gene means the effect produced by other genes, the assumption of a loss still has no advantage over the alternative view that a mutation is due to a change of some sort in the gene. Furthermore, the occurrence of mutation in the reverse direction (omitting the special case of bar reversion), while not sufficiently established as yet, is in better accord with the view that genes may mutate by a change in their constitution without that change being necessarily a loss of the whole gene. And finally, the evidence from multiple allelomorphs seems more consistent with the view that each is due to a change in the same gene.

The theory of the gene as here formulated, regards the wild type genes as specific elements in the chromosomes, that are relatively stable over long periods. There is at present no evidence that new genes arise except by changes in the constitution of the old genes. The total number of the genes remains on the whole constant over long periods. Their number may be changed, however, by a process of doubling the full set of chromosomes and perhaps in other similar ways. The effect of changes of this sort will be considered in later chapters.

CHAPTER VII

THE LOCATION OF GENES IN RELATED SPECIES

DE VRIES' mutation theory quite apart from its special interpretation discussed in an earlier chapter postulates that "elementary" species are made up of a large number of identical genes; and that their differences are due to different recombinations of these genes. The more recent work on hybridizing related species has furnished evidence bearing on this theory.

The most obvious way to study the problem would be to cross species and determine in this way, if possible, whether they are made up of the same number of homologous genes, but several difficulties stand in the way. Many species cannot be crossed, and some of those that can be crossed produce sterile hybrids. Nevertheless, a few species are fertile *inter se,* and some of them also give fertile hybrids. Even then, another difficulty arises, namely, the identification in the two species of the characters that behave as Mendelian pairs; for the differences that serve to distinguish one species from another species are dependent on a multitude of factors in each case. In other words, it is rare to find two well-marked species in which any single difference is due to one differential factor. Mutant differences of recent origin in one or in both species must be resorted to for the necessary evidence.

There are several cases in plants and two at least in animals where species having mutant types have been

crossed with other species, and produced fertile offspring. These, when inbred, or back-crossed, have furnished the only crucial evidence concerning the allelomorphic relation of genes in different species.

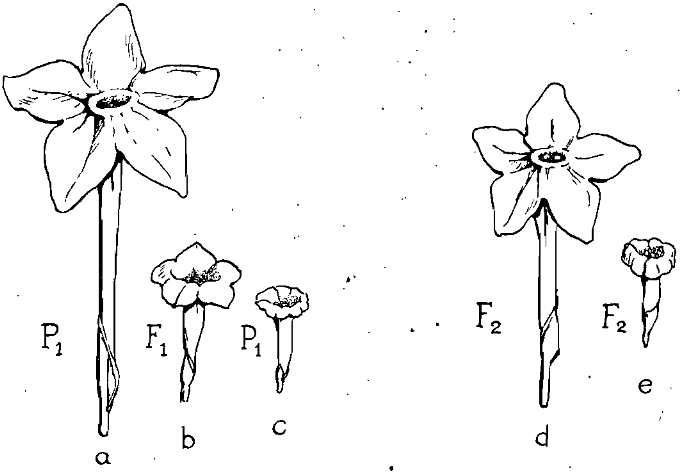


FIG. 53.

Cross between two species of tobacco, Nicotiana Langsdorffii and N. alata. In a and c the two original types of flowers are shown, and in b the hybrid type. In d and e, two of the recovered types in F_2 are shown. (After East.)

East crossed two species of tobacco, Nicotiana Langsdorffii and N. alata (Fig. 53). One plant with white flowers was a mutant type. Despite the wide variability of many characters in the second generation, the white flowers appeared in one-fourth of the individuals of this generation. The mutant gene of one species behaved toward a gene of the other species in the same way as it behaves with its own normal partner.

Correns crossed Mirabilis Jalapa with M. longiflora. A recessive mutant of Jalapa (chlorina) was used. This

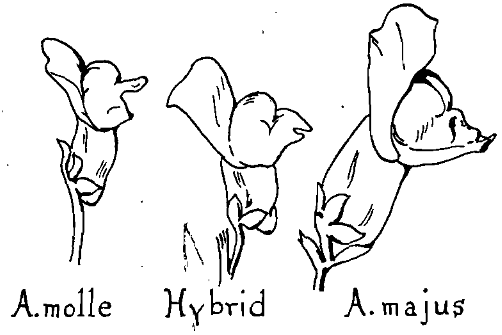


FIG. 54.

Two species of snapdragon, Antirrhinum molle and A. majus with the hybrid between them. (After Baur.)

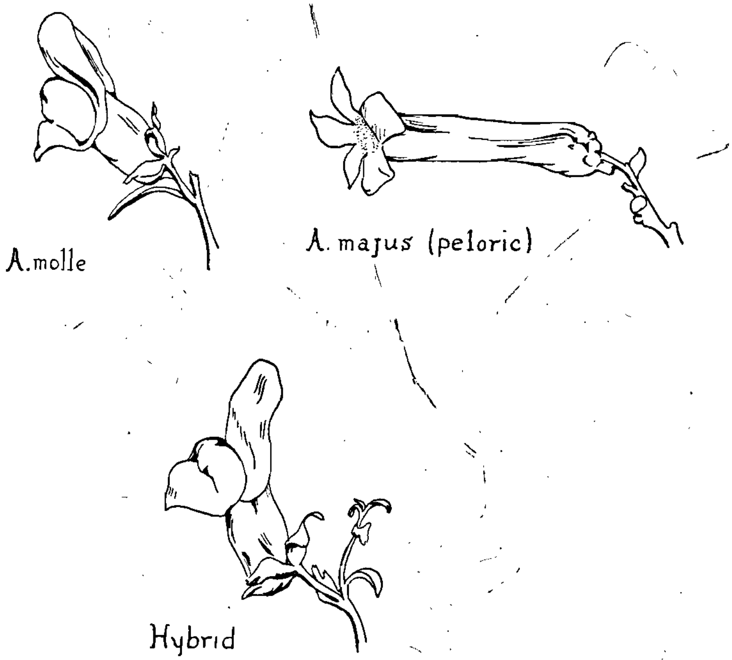


FIG. 55.

A bilateral type of flower of Antirrhinum molle by a peloric type of A. majus, which, when crossed, gives the hybrid "wild" type seen below. (After Baur.)

character reappeared in almost one-quarter of the individuals in the second generation.

Baur crossed two species of snapdragon, Antirrhinum majus and A. molle (Fig. 54). He used at least five

FIG. 56.

Types of F_2 flowers from the cross shown in Fig. 55. (After Baur.)

mutant types of A. majus and recovered them in the second generation in the expected number of individuals (Fig. 55 and 56).

Detlefsen crossed two species of guinea pigs, Cavia porcellus and C. rufescens. The hybrid females (the hybrid males are sterile) were mated to C. porcellus males

with mutant characters, seven in all. The mutant characters were inherited in the same way as in C. porcellus. This result again shows that the two species carry some identical loci. The results do not show, however, that identical mutants exist in the two species, for no mutant races with characters similar to those of porcellus have been studied.

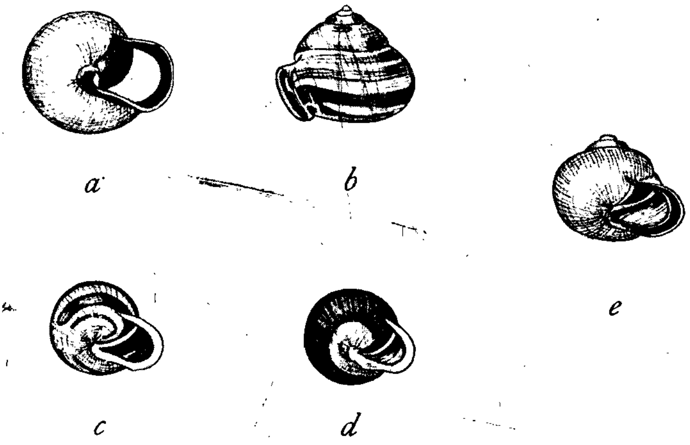


Fig. 57.

a, Helix nemoralis, 00000, yellow, Zurich type; *b*, ditto 00345, reddish (Aarburger type); *c*, typical H. hortensis, 12345; *d*, ditto; *e*, hybrid 00000. (After Lang.)

One of the clearest cases where the characters of one species behave toward the characters of the other species in the dominance-recessive relation as do the same character-pairs within the species is described by Lang in his experiments with two wild species of snail, Helix hortensis and H. nemoralis (Fig. 57).

There are two wild species of Drosophila that are so much alike externally that they were put into the same species. One is now called D. melanogaster, the other D.

simulans (Fig. 58). Careful scrutiny shows them to be different in many ways. They cross with difficulty and the hybrids produced are completely sterile.

Forty-two mutant types are now known in D. simulans. These fall into three linkage groups.

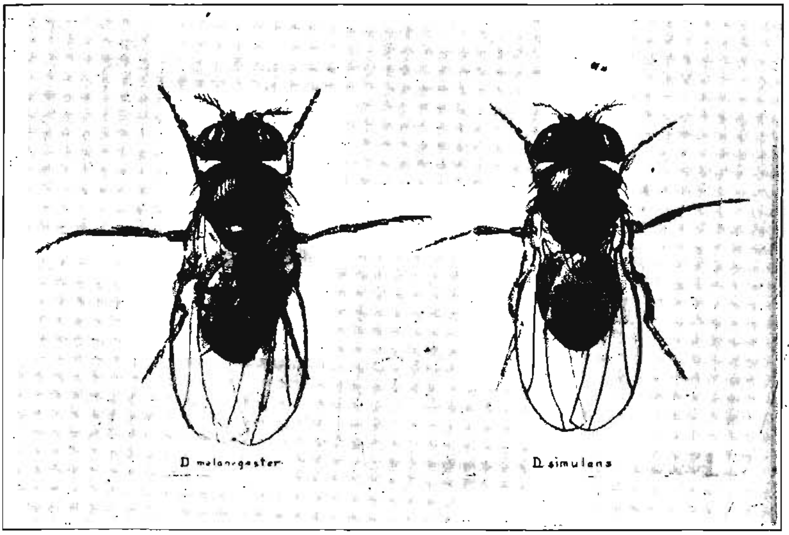


FIG. 58.
Drosophila melanogaster to the left, and D. simulans to the right; both males.

Twenty-three of these recessive mutant genes in simulans are recessive in the hybrid, and 65 recessive mutant genes of melanogaster have also been shown to be recessive in the hybrid. This result means that each species carries the standard or wild type gene of each of the recessive genes of the other species.

Sixteen dominant genes have also been tested. All but one produced nearly the same effect in the hybrid that they produce within their own species. This means that

sixteen normal genes are recessive to the dominant mutant genes of the other species.

Mutants of simulans have been mated to mutants of melanogaster. In twenty cases tested, the mutant character proved to be the same.

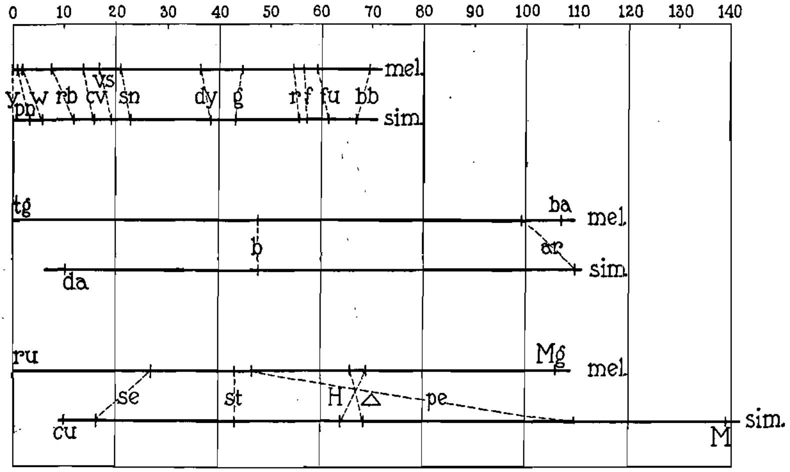


FIG. 59.

Chart showing, above, the corresponding loci of identical mutant genes of the first or X-chromosome in Drosophila melanogaster and in D. simulans, similarly, in the middle, of the second chromosome; and, at the bottom, of the third chromosome. (After Sturtevant.)

This last result establishes the identity of the mutants in the two types, and enables one to discover whether they lie in the same linkage series, and in the same relative position in each series. The chart (Fig. 59) shows by the connecting dotted lines the relative position of the loci of identical mutants so far worked out by Sturtevant. In chromosome-I there is a remarkable agreement. In chromosome-II only two identical loci have been determined. In chromosome-III the agreement is not complete. It can

probably be explained on the assumption that a large section of this chromosome has been reversed, and the corresponding loci are in inverse order.

These results of Sturtevant's are not only important in themselves, but help to make probable the view that similar mutants in different species that occupy the same relative position in the linkage series, are identical mutants, but unless their identity can be tested by crossing,

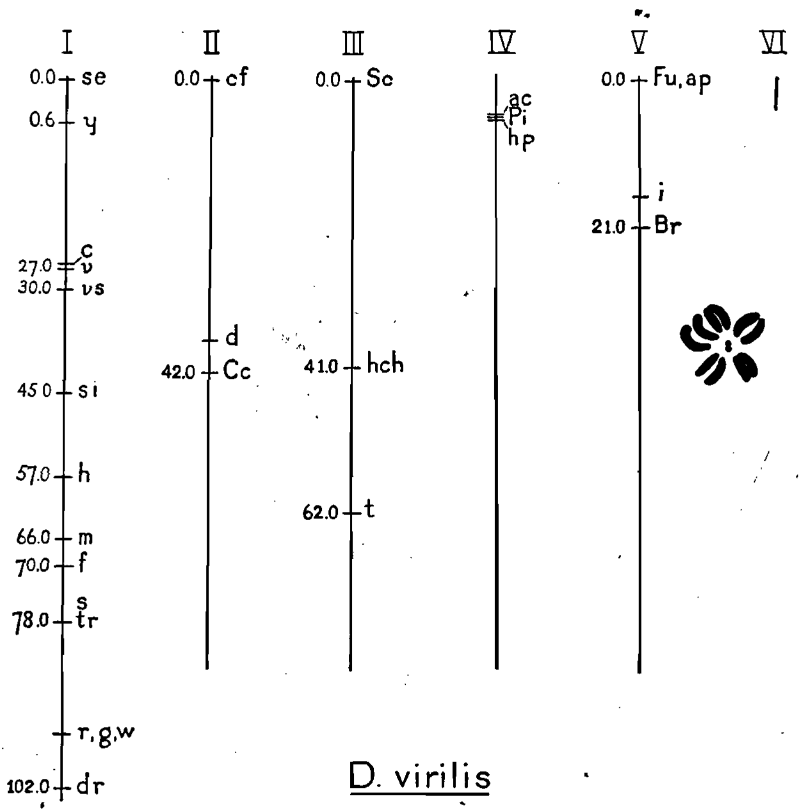


Fig. 60.

Chart of the location of the mutant genes in the six chromosomes of Drosophila virilis. (After Metz and Weinstein.)

as in the case of D. melanogaster, and D. simulans, there may always remain some doubt as to their identity, because similar mutant types that are not identical are

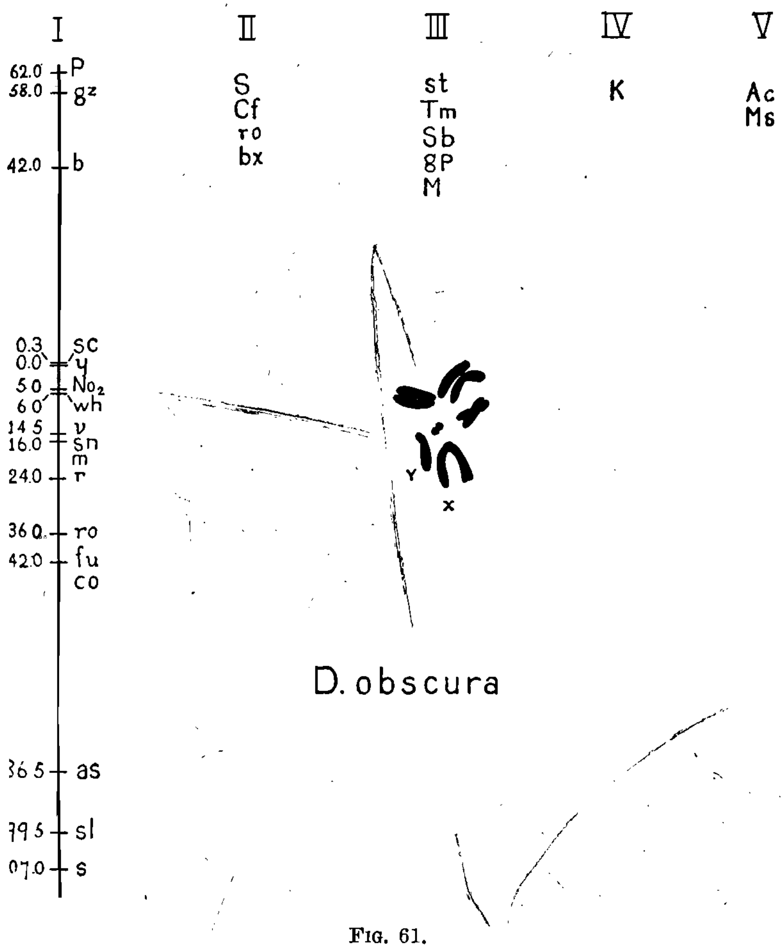


FIG. 61.

Chart of the location of the mutant genes in the chromosomes of Drosophila obscura. The loci corresponding with those of D. melanogaster are sc=scute, y=yellow, No_2=Notch, wh=white. (After Lancefield.)

known, and sometimes these lie near together in the same linkage group.[1]

In two other species of Drosophila the work has progressed to a point where the comparisons are at least very interesting. In Drosophila virilis, Metz and Weinstein have determined the location of several mutant genes, and Metz has compared the order of the series with that of D. melanogaster. The chart (Fig. 60) shows that there are five apparently similar mutants in the sex-chromosome that stand in the same order as those of melanogaster, *viz.,* yellow (y), cross-veinless (c), singed (si), miniature (m), forked (f).

Another species, Drosophila obscura, has a genetic sex-chromosome twice as long as that of melanogaster (Fig. 61). It is probably significant that the four characteristic mutant types, yellow, white eyes, scute, and notch wings, that lie in the middle of this long sex-chromosome, are identical with the same mutant characters of D. melanogaster that lie at the end of the shorter sex-chromosome of melanogaster and simulans. The interpretation of this relation is still being carefully studied by Lancefield.

These and other results should make us extremely cautious in drawing phylogenetic conclusions from inspection alone of the chromosome groups; for, it follows from the Drosophila evidence that very closely related species may have their genes arranged in a different order in the same chromosomes. Similar groups of chromosomes may at times contain different assortments of genes. Since it is the genes, and not the chromosomes as such, that are important, the final analysis of the hereditary construction must be determined by genetics rather than by cytology.

[1] By taking into account more than a single effect of each gene the identification may be made more probable.

CHAPTER VIII

THE TETRAPLOIDS, OR FOURFOLD TYPE

THE chromosomes have been counted in more than a thousand species of animals and probably in as many or more species of plants. In two or three species only one pair of chromosomes is present. At the other extreme there are species with over one hundred chromosomes. No matter how many or how few the chromosomes, the number is found to be constant for each species.

It is true that irregularities in the distribution of the chromosomes occasionally take place. Most of these irregularities are, as a rule, automatically straightened out in one or another way. It is also true that, in one or two cases, a slightly variable number of chromosomes may occur, as in Metapodius where one or more small, extra chromosomes, sometimes the Y-chromosomes, sometimes another chromosome called the M-chromosome, may or may not be present (Fig. 62). As Wilson has shown, these chromosomes may, perhaps, be looked upon as indifferent bodies that have lost their importance, since there are no corresponding variations in the characters of the individuals.

It is known, furthermore, that chromosomes may join together, decreasing the number by one or more, but the totality of the genes is still preserved, and this also holds for cases where a chromosome may break, increasing for a time at least the number by one.[1] Finally, there are

[1] The occasional breaking apart of chromosomes in Oenothera has been described by Hance. In the moth Phragmatobia, and in other moths also, Seiler has described several cases where certain chromosomes that are united

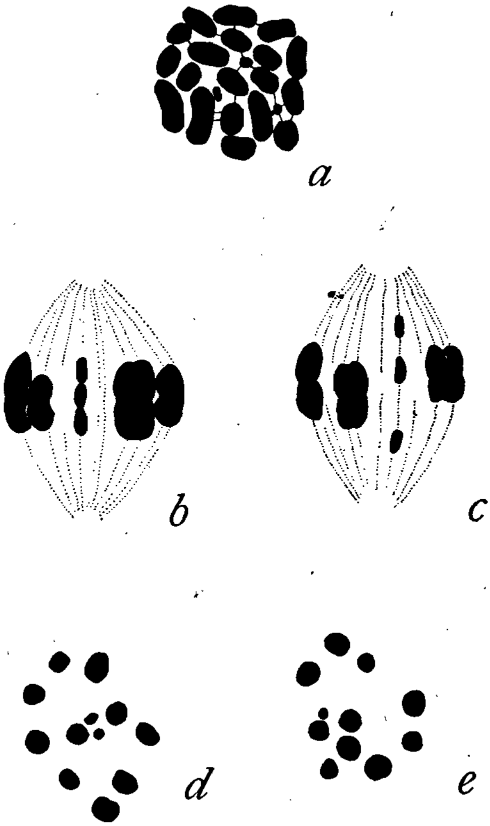


FIG. 62.

Chromosomes of Metapodius. *a*, spermatogonial group with three small m-chromosomes; *b* and *c*, side view of spermatocytes, conjugation of three *m*'s, two pass to one pole, one to the other, as seen in *d* and *e* (anaphase plates of *c*). (After Wilson.)

species where the female has one chromosome more than the male, and there are other species where the

in the eggs and sperms, are separate in the embryonic cells. In the bee each chromosome is supposed to break into two parts in all of the somatic cells. In some of the tissue cells of flies and other animals the chromosomes may divide without the cell dividing and in this way become doubled or quadrupled.

reverse may be true. All these situations have been extensively studied, and are familiar to every student of the cell. The occurrence of such cases does not invalidate the general statement, *that the number of the chromosomes is constant and characteristic of each species.*[2]

In recent years an ever increasing number of cases has been reported in which individuals have suddenly appeared that have double the number of chromosomes characteristic of the species. These are the fourfold types, or tetraploids. Other multiple types have also been found, some arising spontaneously, others derived from the tetraploids. We speak of these collectively as polyploids. Of these polyploids, the fourfold group is in many ways the most interesting.

In animals there are only three cases of tetraploidy that are certainly known. The parasitic threadworm of the horse, Ascaris, occurs in two types, one with two and one with four chromosomes, respectively. These two varieties are like each other, even as to the size of their cells. The chromosomes of Ascaris are regarded as compound and as formed by the union of a number of smaller chromosomes sometimes called chromomeres. In the cells of the embryo that will become body-cells, each chromosome breaks up into its constituent elements (Fig. 63, a, b, d). These are constant in number or approximately so,

[2] Della Valle and Hovasse have in recent years denied that the number of chromosomes is constant in different tissue cells. In so far as the conclusions are based on an examination of the somatic cells of Amphibia that have a large number of chromosomes difficult to identify with accuracy, their results do not suffice to overthrow the overwhelming number of observations on other forms (and even on some Amphibia) where the number of the chromosomes can be accurately determined.

It is also known that in certain tissues the number of the chromosomes may be doubled or quadrupled, either by failure of cells to divide when the chromosomes divide, or else by the chromosomes breaking up into a constant number of parts. These are special cases that do not affect the general situation.

and there are in all about twice as many elements in bivalens as in univalens. This supports the view that there are twice as many chromosomes in one type as

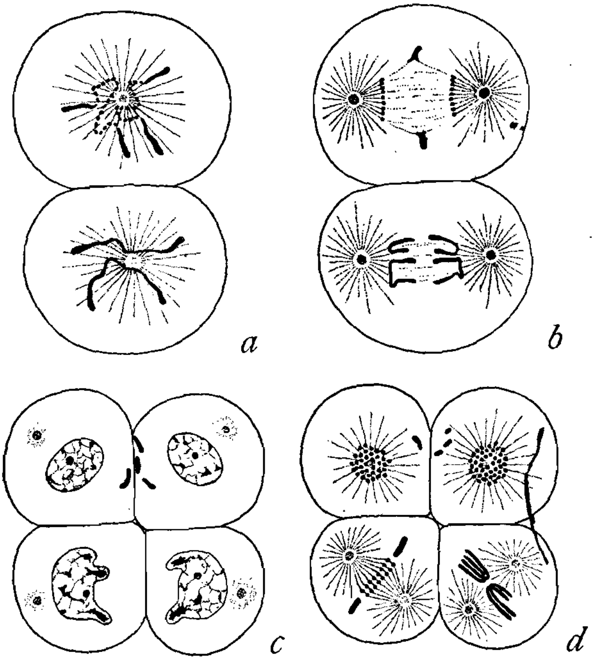


FIG. 63.

First and second cleavages of the egg of Ascaris univalens with two chromosomes. In *a* and *b* the fragmentation of the two chromosomes in one of the cells is shown. In *d*, three cells show fragmented chromosomes, while in the fourth cell the chromosomes are intact. The latter gives rise to the germ-cells. (After Boveri.)

in the other, rather than that bivalens has arisen through the halving of the univalens chromosomes.

One form of the brine shrimp, Artemia salina, is, according to Artom, a tetraploid. There are two races, one with 42 chromosomes, the other with 84 chromosomes (Fig. 64). The latter propagates by parthenogenesis

Under these circumstances it is not difficult to imagine that the tetraploid originated in a variety that was already parthenogenetic, for, should an egg-cell double the number of its chromosomes by the retention of one of its polar bodies, or become double through the chromosomes failing to separate after the first division of a nucleus, the double condition might continue to perpetuate itself.

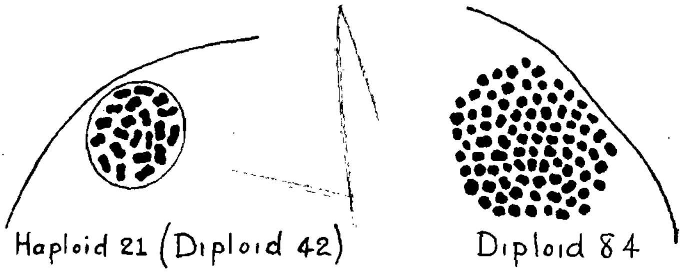


FIG. 64.

The chromosomes, in reduced number, of the diploid and tetraploid races of Artemia salina. (After Artom.)

One of the first tetraploids in plants was discovered by de Vries, and named Oenothera gigas (Fig. 42). It was not known, at first, that this giant was a fourfold chromosome type, but de Vries saw that it was stouter than plants of the parent species (Lamarck's evening primrose) and different in many other minor characteristic details. Its chromosome number was later made out.

Lamarck's evening primrose (Oenothera Lamarckiana) has 14 chromosomes (haploid 7). The giant form O. gigas has 28 chromosomes (haploid 14). The two chromosome groups are drawn in Fig. 65.

Gates has made measurements of the cells of different tissues. The epidermal cells of the anthers of gigas

have almost four times the volume of the normal type; those of the stigma three times the volume; those of the petals twice the volume and the pollen mother cells are about one and a half times larger. The nuclei of the latter have, in gigas, twice the volume of the parent type. The cells in the two types also differ sometimes markedly in their superficial dimensions. Most species of evening primroses have 3-lobed discoidal pollen grains, some of those of gigas are 4-lobed.

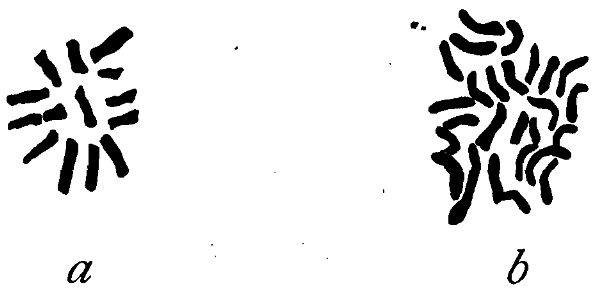


Fig. 65.

a, The fourteen diploid chromosomes of Oenothera Lamarckiana; *b*, the twenty-eight diploid chromosomes of O. gigas.

The maturation of the pollen mother cells has been studied by Gates, Davis, Cleland, and Boedijn. Gates reports that in O. Lamarckiana there are, as a rule, 14 pairs of bivalent chromosomes (gemini) in the giant. At the first maturation division, half of each bivalent goes to each daughter cell. At the second division each chromosome splits lengthwise and gives 14 chromosomes to each pollen grain. A similar process presumably occurs in the ripening of the ovules. Davis describes the chromosomes of O. Lamarckiana that emerge from the synaptic tangle as stuck together somewhat irregularly and not strictly in side to side union. Later they move toward one

or the other pole bringing about reduction. Cleland has recently described an end-to-end union of the chromosomes of another diploid species, Oenothera franciscana, as they enter the maturation spindle (Fig. 66). Some of

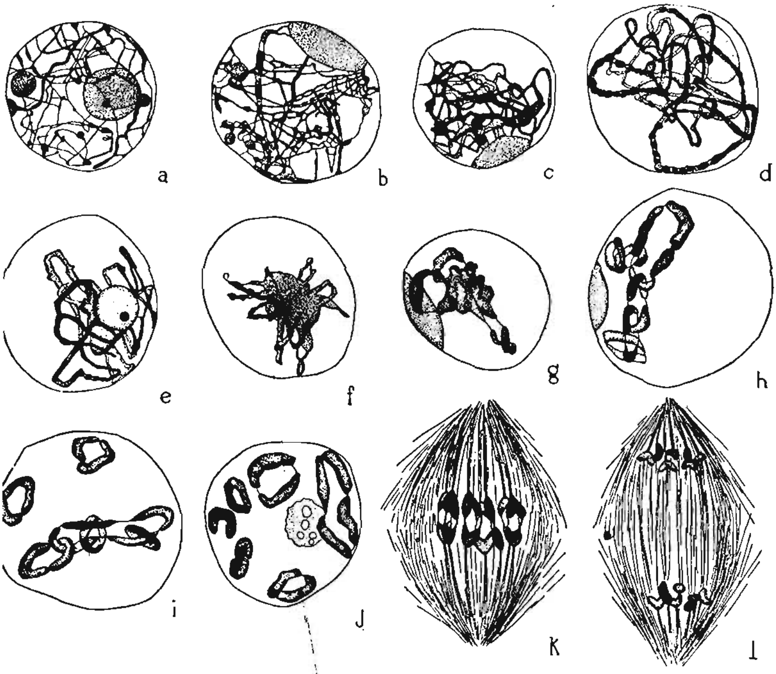


FIG. 66.
The maturation of the pollen cells in Oenothera franciscana. (After Cleland.)

the earlier figures of Davis had also to some extent indicated an end-to-end union.

In other monoecious flowering plants tetraploids have also been found in recent years. It is obvious why these occurrences should be more frequent in monoecious species than in species with separate sexes; for, in the

former, eggs and pollen are produced on the same plant. Hence if a plant has started as a tetraploid, it will produce both egg-cells and pollen-cells with a diploid number of chromosomes. Self-fertilization will give tetraploids again. On the other hand, in animals or plants with separate sexes the eggs of one individual must be fertilized by sperm from another individual. Now, if a tetraploid female should arise, her ripe eggs, with the diploid number of chromosomes, will ordinarily be fertilized by the haploid sperm from a normal male, with the result that a threefold type, or triploid is formed. From a triploid the chance of recovering a tetraploid again is very small.

The tetraploids that have arisen in pedigreed cultures furnish more accurate information as to their origin than do tetraploids found accidentally. There are, in fact, other records where tetraploids have arisen under controlled conditions. In Primula sinensis, Gregory has found two giant types, one of which appeared in a cross between two diploid plants. Since the parent plants contained known genetic factors, Gregory was enabled to study the inheritance of the characters in the fourfold type. His results left him undecided as to whether they indicated that a given member of each of the four like chromosomes unites with a specific mate or equally with any member of its group. Muller's analysis of the same data indicates the latter as the more probable conclusion.

Winkler has obtained a giant nightshade (Solanum nigrum) and a giant tomato (Solanum lycopersicum) through the intermediate process of grafting, which has in itself, so far as known, no direct relation to the production of the double forms.

The tetraploid nightshade was obtained in the following way. A piece of a young tomato plant was grafted into a young nightshade plant from which the axial buds were then removed. A cross cut was made, ten days later,

at the graft level (Fig. 67). Adventitious buds grew up from the callus tissue of the exposed surface. One of these plants was a chimaera, *i.e.*, a plant part of whose tissue was nightshade and part tomato. It was removed and propagated. Some of the axial buds of the new plant

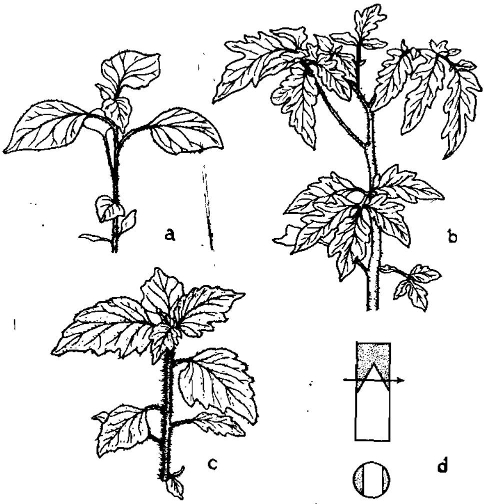


FIG. 67.

a, Seedling of Solanum nigrum. b, Seedling of Solanum lycopersicum. c, Solanum tubingense—graft-hybrid. d, method of grafting. (After Winkler.)

had a tomato epidermis and a nightshade core. These branches were then isolated and planted. The plantlets differed from other chimaeras known to be diploid, which created a suspicion that the new type might have a tetraploid core, which was confirmed by examination. The tops of these chimaeras were cut off, and the axial buds of the basal half removed. From the adventitious buds of the

callus, young plants were obtained that were tetraploid throughout. One of these gigas nightshade plants is shown in Fig. 68, to the right, and a normal (diploid) or parent type, to the left; a flower of gigas is shown above to the right in Fig. 69 and the parent type to the left. A seedling gigas is shown and a seedling of the parent type above left, Fig. 69.

FIG. 68.

Normal diploid parent plant of solanum to the left, and tetraploid to the right. (After Winkler.)

The differences in the cells of some of the tissues are shown in Fig. 69. The palisade cells of the leaf of the gigas type and the corresponding cells of the parent type are shown below to the left; the guard cells of the gigas stomata and those of the parent type are shown below to the right; the hairs of the gigas form and those of the parent are shown at the bottom to the right; the pith cells of the giant are correspondingly larger than those of the normal plant. The pollen grains of the giant are repre-

sented in the middle to the right and those of the parent type to the left.

A tetraploid tomato plant, also, was obtained as follows. A piece of a young tomato plant was grafted on to a stock of nightshade in the usual way (Fig. 67). After union

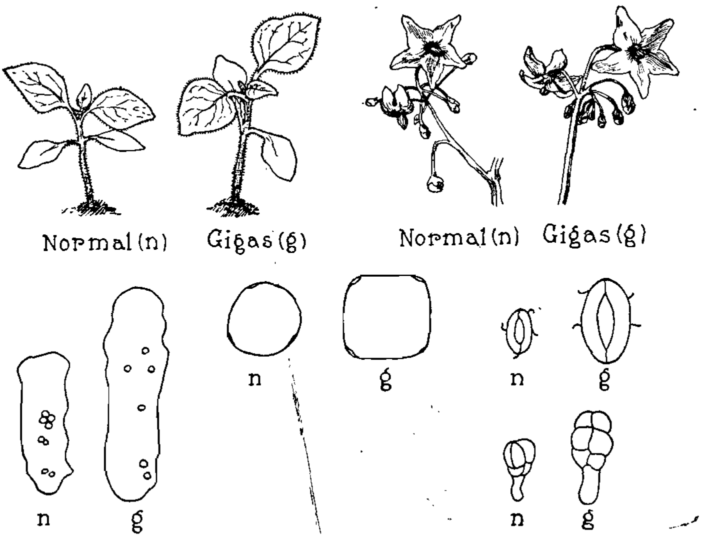


FIG. 69.

Diploid and tetraploid seedlings and flowers of the nightshade are shown above, and tissue cells below. Above to left, seedlings; above to right, flowers; below to left, palisade cells; in middle, pollen grains; to right stomata, above, and hairs below. (After Winkler.)

had been perfected, a cut was made across the union of the two plants and the axial buds removed from the stock. From the cut surface, young buds developed in the callus tissue. These were removed and planted. One of these had an epidermis of nightshade cells and a core of tomato cells. It was found on further examination that the epidermal cells were diploid and the cells of the core were

tetraploid. In order to obtain, from this composite plant, a tetraploid in all of its parts, the stem of a young plant was cut across and the axial buds below the cut were removed. New adventitious buds appeared on the cut surface which were, for the most part, made up of the

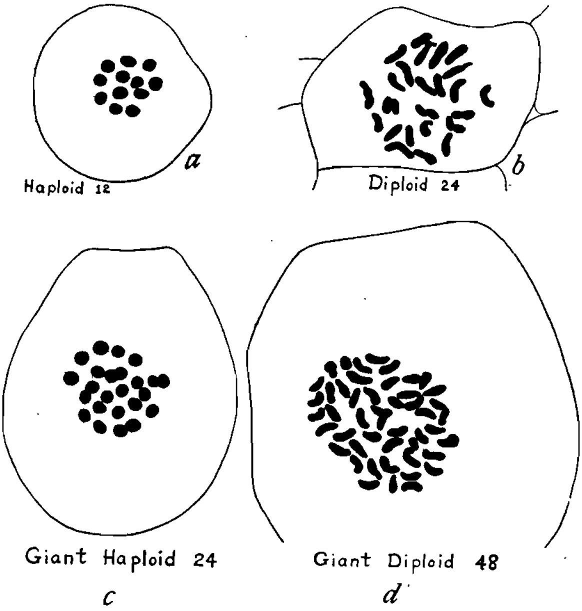


FIG. 70.

a, Haploid; *b,* diploid cell and chromosomes of nightshade; *c,* hap loid, and *d,* diploid cell and chromosomes of tetraploid night-shade. (After Winkler.)

tomato tissues both within and without. The giant tomato plant differs from the parent plant in the same way as does the giant nightshade from its parent.

The diploid nightshade has 24 chromosomes, its haploid number is 12; the tetraploid has 48 chromosomes, and its haploid number is 24 chromosomes. The diploid tomato has 72 chromosomes (haploid 36). The tetraploid

tomato has 144 chromosomes (haploid 72 chromosomes). These chromosomes are shown in Figs. 70 and 71.

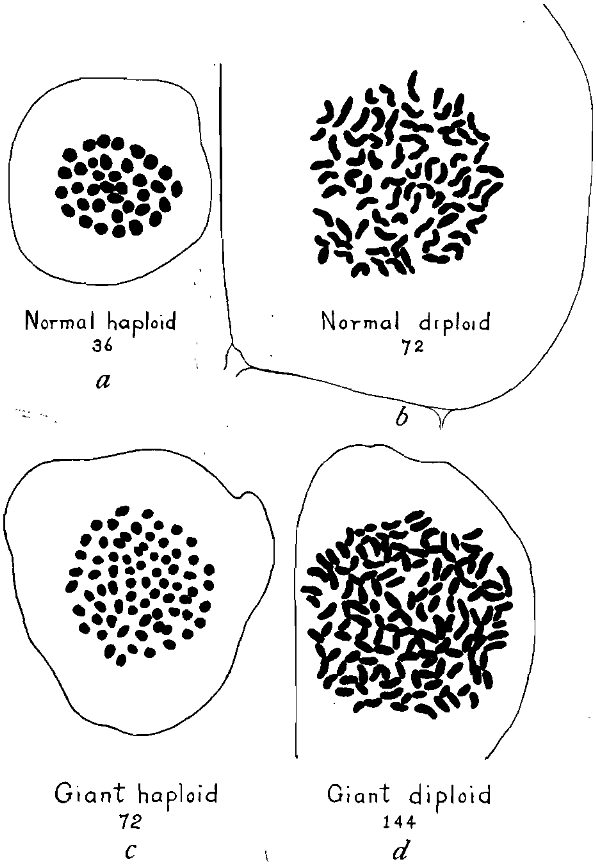


FIG. 71.

a, Haploid; *b*, diploid cell and chromosomes of tomato; *c*, haploid, and *d*, diploid cell and chromosomes of tetraploid tomato. (After Winkler.)

As has been said, there is no obvious relation in these cases, as far as known, between grafting and the formation of tetraploid cells in the callus. How these cells arise is uncertain. It is possible that two cells of the callus fuse

together, as Winkler at one time thought probable, but it seems more likely that the tetraploids arise by the suppression of the cytoplasmic division of a dividing cell, which would thereby double the number of its chromosomes. Such a tetraploid cell might form the whole or only the core, or any other part of a young plant.

A tetraploid of the common Jimson weed (Datura stramonium) (Fig. 72 below) was found by Blakeslee,

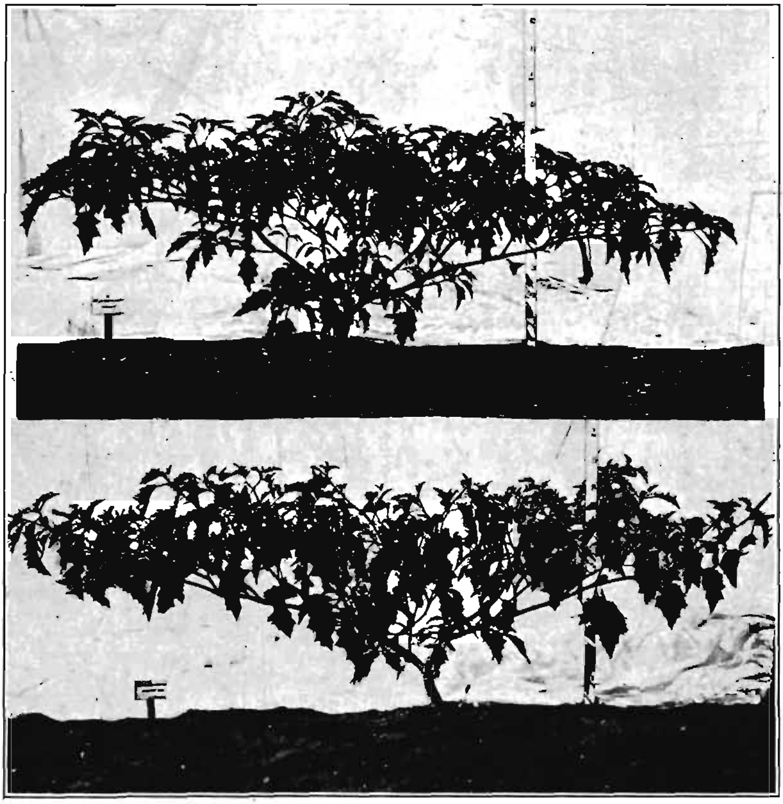


FIG. 72.

Diploid plant of Datura stramonium, above, and tetraploid, below. (After Blakeslee.)

Belling, and Farnham. In appearance it is described as differing in several respects from the diploid type. The differences in the capsule, flower, and stamens in the diploid (second column) and tetraploid (fourth column) are shown in Fig. 73.

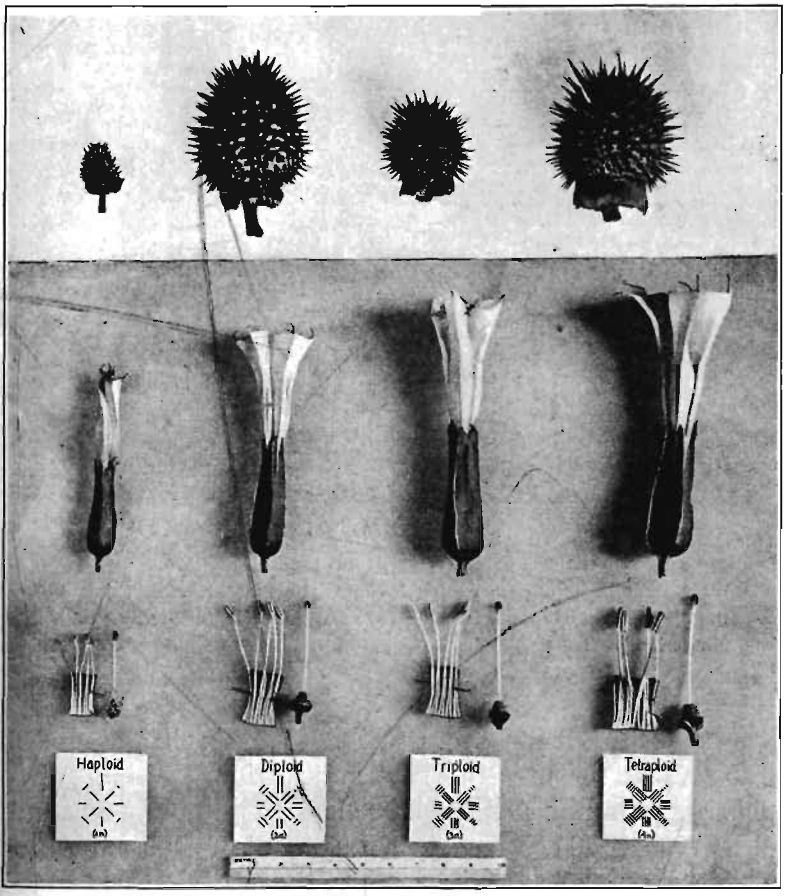


FIG. 73.

Capsules, flowers, and stamens of haploid, diploid, triploid, and tetraploid D. stramonium. (After Blakeslee, in Journal of Heredity.)

Belling, and Farnham. In appearance it is described as differing in several respects from the diploid type. The differences in the capsule, flower, and stamens in the diploid (second column) and tetraploid (fourth column) are shown in Fig. 73.

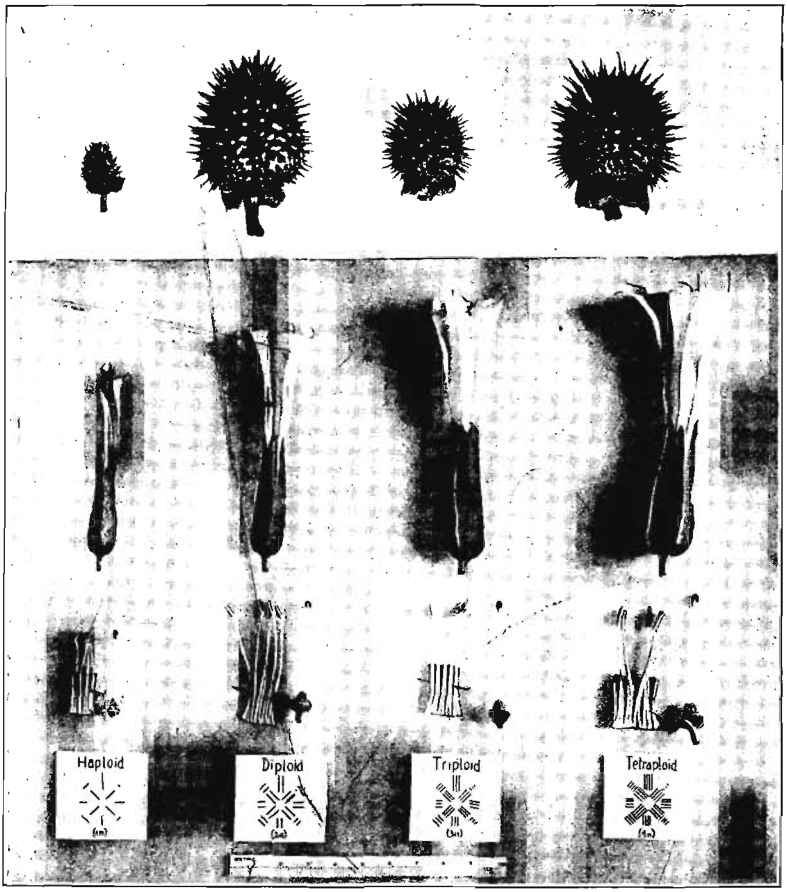
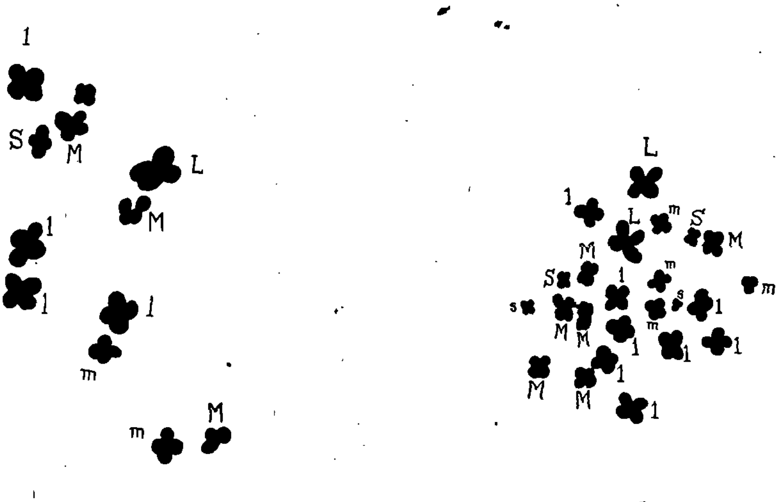


FIG. 73.

Capsules, flowers, and stamens of haploid, diploid, triploid, and tetraploid D. stramonium. (After Blakeslee, in Journal of Heredity.)

The diploid plant has 12 pairs of chromosomes (24 chromosomes) which according to Belling and Blakeslee can be arranged in six sizes (Fig. 74), namely, large (L and l), medium (M and m), and small (S and s), or 2 (L+4l+3M+2m+S+s). The formula for the haploid



a *b*

FIG. 74.

a, Second metaphase chromosome group of diploid Datura stramonium with 12 chromosomes (each constricted); and *b*, corresponding group of tetraploid with 24 chromosomes. (After Belling and Blakeslee.)

group is L+4l+3M+2m+S+s. These chromosomes, when about to enter the first maturation division (prophase), form pairs of rings or else are united by one end (Fig. 75, second column). One conjugant of each pair then moves to one pole and its mate to the opposite pole. Preparatory to the second maturation division, each chromosome constricts, producing the appearance shown in Fig. 74b. One constricted half passes to one pole of the spindle,

the other half to the other pole. Each daughter cell gets 12 chromosomes.

The tetraploid has 24 pairs or 48 chromosomes. Prior to their entrance into the first maturation spindle they come together in fours (Fig. 76 and Fig. 75). The differ-

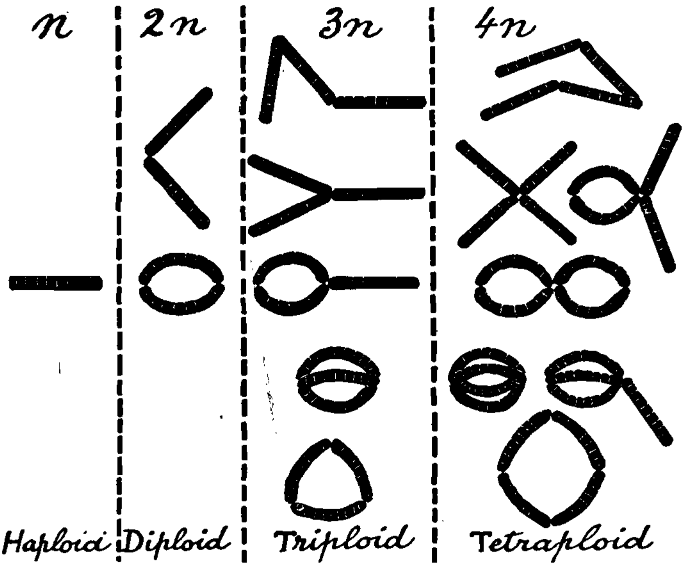


FIG. 75.

Methods of conjugation of the chromosomes in diploid, triploid, and tetraploid types of Datura stramonium. (After Belling and Blakeslee.)

t ways in which these chromosomes are combined in ɜse quadrivalent groups is shown in these figures. They ter the first maturation spindle in approximately this ıdition. At the first maturation division two members each quadrivalent pass to one pole and two to the opsite pole (Fig. 75). Each pollen grain has 24 chromomes. Occasionally, however, three chromosomes may ss to one pole and one to the other.

The 24 chromosomes of the tetraploid at the second maturation division are shown in Fig. 74. They resemble those of the diploid at the same stage. Half of each passes to one pole, half to the opposite pole. Belling records that in 68 per cent the distribution is regular, *i.e.*, 24 to each pole (24+24). In 30 per cent of cases the dis-

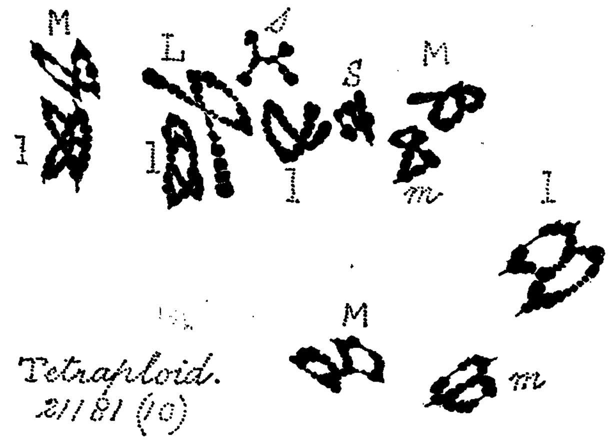


FIG. 76.

Conjugation of the chromosomes of the tetraploid of Datura stramonium. Four like chromosomes unite to make up each group. (After Belling and Blakeslee.)

tribution gives 23 at one pole and 25 at the other (23+25). In 2 per cent there were 22 at one pole and 26 at the other. In one case the distribution was 21-27. The result shows that irregularities of distribution are not uncommon in the tetraploid Datura. A further test of this was made by self-fertilizing a tetraploid. The progeny was grown to maturity and the chromosomes in their germ-cells counted. The number of chromosomes in 55 of the plants was 48; in five plants it was 49; in one plant it was 47; in another it was 48 (?). If the distribution in the egg-cells is like that in the pollen cells, it follows that the

germ-cells with 24 chromosomes are those most likely to survive and function. Some of these plants with more than 48 chromosomes might give new types with still greater irregularities of distribution of the chromosomes, owing to the additional extra chromosomes.

FIG. 77.

a, Euchlaena perennis, first maturation division, prophase; with 19 bivalents and two single chromosomes, a¹, Metaphase of last. a², Anaphase of same. b, Zea mays, first maturation prophase with ten bivalents. c, Euchlaena mexicana, first maturation division, prophase, with ten chromosomes. ab, Hybrid (F_1) between E. perennis and Zea mays, prophase of first maturation division with 3 trivalent, 8 bivalent, and 5 single chromosomes. ab¹ Same as last, late anaphase of first maturation division. (After Longley.)

A tetraploid Narcissus has been reported by de Mol. The diploid species has 14 chromosomes (7 pairs) while two cultivated varieties were found to have 28 chromosomes. De Mol points out that until 1885 the small diploid varieties were chiefly cultivated. Then the larger triploid types appeared and finally about 1899 the first tetraploid was obtained.

The perennial teosinte of Mexico has twice as many chromosomes as the annual teosinte, according to Longley. The perennial Fig. 77a, has 40 chromosomes (n=20) and the annual 20 chromosomes (n=10) Fig. 77c. Longley crossed both of these with corn (maize), that has 20 chromosomes (n=10) Fig. 77b. The hybrid between the annual teosinte and corn has 20 chromosomes. At the maturation stages of the pollen mother cells there are 10 bivalents, and these divide and pass to the poles without any lagging chromosomes. This means that the 10 chromosomes that have come from the teosinte conjugate with the 10 that have come from the corn. When the perennial teosinte is crossed to corn the hybrid has 30 chromosomes. At the ripening of the pollen mother cells of the hybrid the chromosomes are found to be united, some in threes, others in twos; the rest have no partners (Fig. 77ab). This leads to irregularities in the division that follows (Fig. 77ab[1]).

In hermaphroditic or monoecious plants, where the question of sex determination is not involved with differential sex-chromosomes, the tetraploid may be said to be both balanced and stable. By balanced is meant that the numerical relations of the genes is the same as that in the diploid or normal type. By stable is meant that the mechanism of maturation is such that the type, once established, perpetuates itself.[3]

Tetraploids in mosses were produced as early as 1907

[3] Blakeslee used the terms differently.

by Élie and Émile Marchal by artificial means. Each moss plant has two generations, a haploid protonema stage (gametophyte) that produces eggs and sperm-cells and a diploid stage (sporophyte) that produces asexually

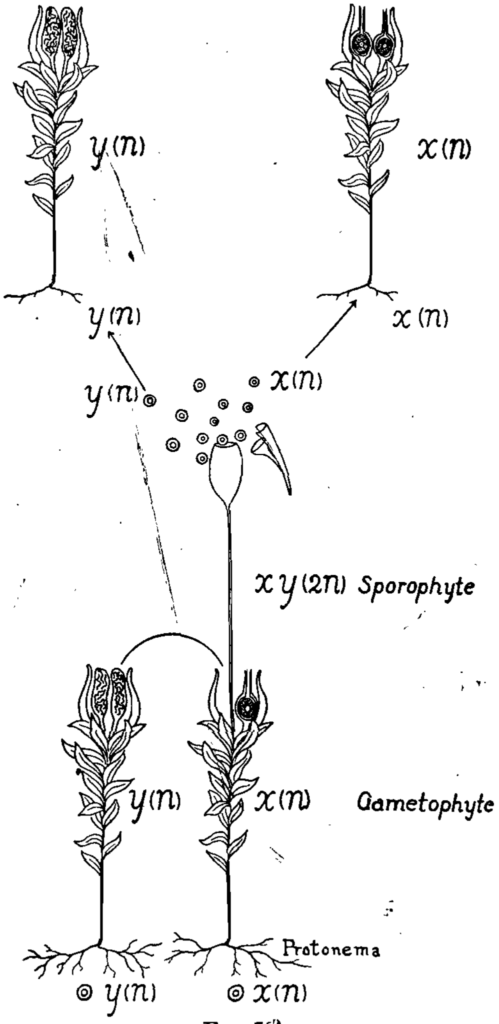


FIG. 78.
Normal life cycle of dioecious moss.

the spores (Fig. 78). Pieces of the sporophyte if kept under moist conditions give rise to threads whose cells are diploid. These become a true protonema that gives rise in time to diploid eggs and diploid sperm-cells. By the union of these germ-cells tetraploid sporophyte plants are formed (Fig. 79). Here the normal haploids have been duplicated by a diploid protonema and moss plant, and the diploid sporophyte has been duplicated by a tetraploid sporophyte.

The Marchals have made comparative measurements of the size of the cells of the normal plants and of those of the tetraploids. In three species the volume of the normal perianth cells to that of the doubles was found to be as 1 to 2.3; 1 to 1.8; and 1 to 2. The volumes of the cells of the normal antheridia in the two types were as 1 to 1.8 and those of the nuclei were about as 1 to 2. The egg-cells were as 1 to 1.9. Measurements of the antheridial organs (that carry the sperm-cells) and of the archegonial organs (that carry the egg) showed in all cases that the double types are longer and broader than are the normal types. It is evident that the increase in size of the double types is due to larger cells and these in turn have larger nuclei, which, other evidence has shown, have in the double types twice as many chromosomes as in the normal type. This was, of course, to be expected from their origin by regeneration from the normal sporophyte.

In the sporophyte generation the mother cells of the 2n spores were to those of the 4n spores about as 1 to 2.

The two maturation divisions in mosses, *i.e.,* the divisions following conjugation of the chromosomes, take place in the sporophyte at the time when the spores are formed—four from each spore mother cell. If, in mosses, the chromosomes carry the genes, the doubling of the chromosomes (tetraploid) in double types is expected to

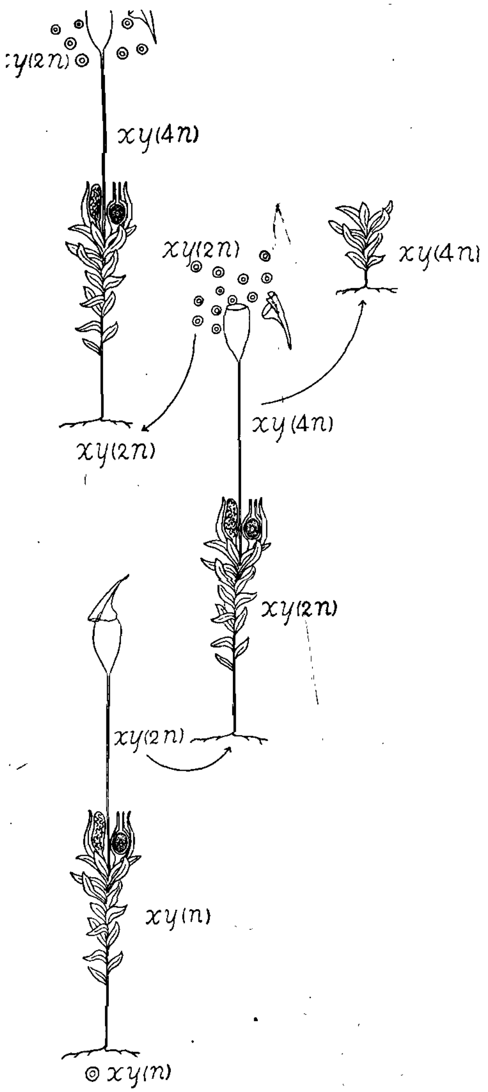


FIG. 79.

Formation of a diploid protonema (2n) by regeneration from a 2n sporophyte of a normal, monoecious moss. By self-fertilization a 2n gametophyte gives rise to a tetraploid or 4n sporophyte. By regeneration from the latter a tetraploid gametophyte is produced.

give ratios different from those in the normal plants. As yet little has been done in this direction, although Wettstein has found clear evidence of genetic inheritance in a few species crosses of mosses, and Allen, in the related group of liverworts, has genetic evidence for two characters of the gametophyte.

In those mosses with separate sexes and in certain liverworts it has been shown by the Marchals, by Allen, by Schmidt, and by Wettstein that the sex-determining elements are sorted out at the time of spore formation. An account of these observations and experiments will be given in the chapter on sex.

There are many important questions for embryology rather than for genetics relating to the size of the cells of tetraploids. In general it may be said that the cells are larger, and frequently twice as large, but there is a good deal of variation in the different tissues in these respects.

The size of the whole plant as well as some of the other peculiarities of the tetraploid are due apparently to the increase in size of its cells. If this is correct, it means that these characteristics are developmental rather than genetic. The way in which tetraploids arise has to some extent been already considered. The methods that have been suggested, as to how the increase in the amount of cytoplasm in the cells of the tetraploids takes place, call for further examination.

If two cells in the germ-track should fuse, and their nuclei then or later unite, a tetraploid cell might result. If the double cell continued to maintain a double volume in the growth period, an egg of twice the normal size would be expected to result. The number of cells of the larger embryo would also be expected to be the same as that characteristic of the normal embryo.

There is, however, another possibility, namely, that the

double germ-cell might not be able to increase to double size in the germ-track of its diploid mother. The egg might not then be any larger than the normal egg, but have twice as many chromosomes. The embryo developing from this egg might not be able to get enough nourishment to increase the size of its cells until the post-embryonic or larval stages were reached, when food is obtainable from the outside. Whether at this late period the presence of a double set of chromosomes in each cell would bring about an enlargement of the cytoplasm of each cell is uncertain. In the next generation, however, the eggs would develop from the beginning with a four-fold set of chromosomes in a tetraploid body, and under these circumstances it is conceivable that the egg might grow to double size before dividing.

It is even less to be expected, perhaps, that an immediate increase in amount of the cytoplasm could take place if the doubling of the chromosomes occurred in a mature egg after it is fertilized. The embryos of animals pass through a rather definite number of cell-divisions before organ formation begins. If an embryo should start as an egg of normal size but with double the number of chromosomes, and if, in consequence of the double number present, cleavages should cease sooner than in the normal egg when organ formation sets in, such a tetraploid embryo would then have cells twice the size of the normal embryo but only half as many cells.

In the flowering plants where ample space and food supply is present in the embryo sac, the development of an egg with a larger amount of cytoplasm may have a more favorable chance to take place.

Tetraploidy as a Means of Increasing the Number of Genes in a Species.

One of the most interesting considerations connected with tetraploids from an evolutionary standpoint is the opportunity they may seem to furnish for increasing the number of new genes. If new and stable types arise through doubling the number of the chromosomes, and if, after doubling, the four like chromosomes should become different in the course of time, so that two become more like each other, and the other two also become more like each other, the tetraploid would then resemble genetically a diploid, except in so far as many of the genes remained unchanged. Many like genes would then be present in four chromosomes of each set, and the expectation for the F_2, when an individual is heterozygous for only one pair of genes, would be a Mendelian ratio of 15 to 1 instead of 3 to 1. Such ratios have in fact been found (wheat, shepherd's purse) but whether tetraploidy accounts for the result or whether doubling has occurred in some other way remains to be determined.

On the whole, it seems that until we know something more as to the way in which new genes arise—if they do now arise—it is rather hazardous to take advantage of tetraploidy as a general explanation to account for a change in number of the genes. It is true that in monoecious plants new types may arise in this way, yet it is improbable that, in animals with separate sexes, tetraploidy could become established (except in parthenogenetic species), because, as has been pointed out above, the tetraploid is lost by crossing to an ordinary or diploid individual and not easily recovered afterwards.

CHAPTER IX

TRIPLOIDS

IN recent work a number of threefold, or triploid, types have also been recorded. Some of these triploids have arisen from known diploid types; others have been found in cultivated plants, while still others have been found in the wild state.

Gates and Anne Lutz described triploid plants of Oenothera (semi-gigas), with 21 chromosomes. Triploids of Oenothera have since been described by de Vries, van Overeem, and others. They are supposed to be produced by the union of a diploid with a haploid germ-cell.

The distribution of the chromosomes of triploids during maturation has been studied by Gates and Geerts and van Overeem. They find that while, in some cases, the chromosomes are rather regularly distributed at reduction, in other cases some of the chromosomes are lost and degenerate. Miss Lutz found in fact great variation in the kind of offspring produced by triploids. Gates records that, in one 21-chromosome plant, the two cells resulting from the first maturation division contained "almost invariably" 10 and 11 chromosomes respectively and only occasionally 9 and 12. Geerts found more numerous irregularities. He describes 7 of the chromosomes going regularly to each pole, while the remaining 7 that were unpaired were irregularly distributed to the poles. This account fits well with the view that 7 conjugate with 7, leaving the remaining 7 without partners. Van Overeem states that in Oenothera, when the triploid serves as the mother plant, the results show that most of the ovules are

functional, regardless of the distribution of the unpaired chromosomes, or, in other words, all or most of the possible different groups of egg-cells survive and may be fertilized. The outcome is a varied assortment of forms with many different combinations of chromosomes. On the other hand, when the pollen of a triploid Oenothera

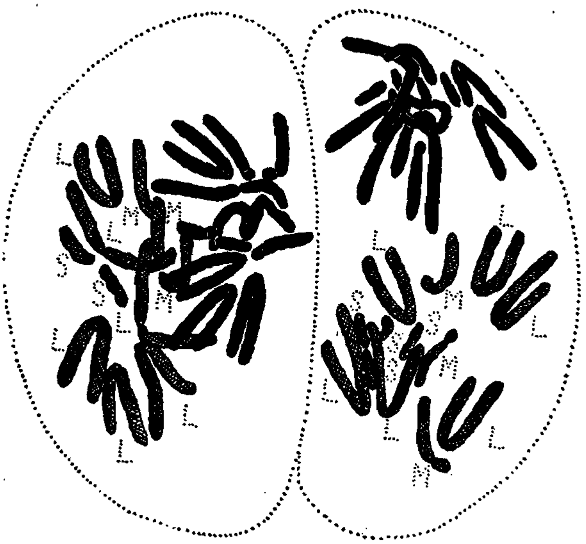


FIG. 80.

Triploid chromosome-group of the pollen mother cell of the Hyacinth. (After Belling.)

is used, the results show that only those carrying 7 or 14 chromosomes are functional. The pollen grains with intermediate numbers are, for the most part, not functional.

Triploid hyacinths have been found under cultivation by de Mol. He states that they are replacing the older types as a result of selection for commerce. Some of their derivatives, with chromosome numbers varying around the triploid, constitute a considerable part of modern cul-

tivated types. Since hyacinths are usually reproduced by bulbs, any particular form can be perpetuated. De Mol has studied the maturation of the germ-cells, both of the normal and the triploid hyacinths (Fig. 80). The normal diploid type has 8 long, 4 medium, and 4 short chromosomes. The haploid germ-cell contains 4 long, 2 medium, and 2 short chromosomes. Both de Mol and Belling have pointed out that the "normal" may be already a tetraploid, since in the reduced group there are two chromosomes of each size. If so, the so-called triploid may possibly be a double triploid, since it has 12 long, 6 medium, and 6 small chromosomes.

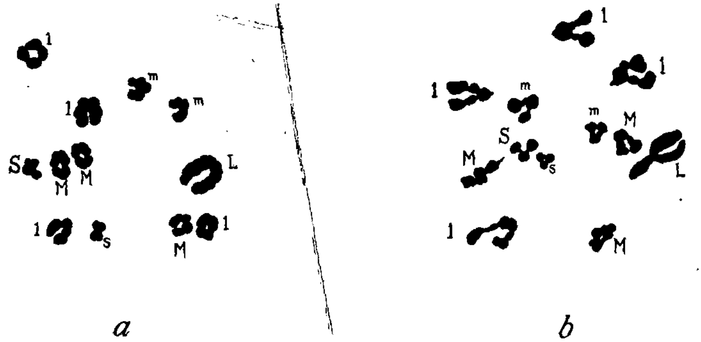


FIG. 81.

a, Reduced chromosome group of diploid Datura; *b*, reduced chromosome group of triploid Datura. (After Belling and Blakeslee.)

Belling has also studied the maturation divisions of a triploid variety of Canna. The chromosomes of each type conjugate in threes. When the chromosomes separate two of each triplet pass as a rule to one pole and one to the other pole, but since the distribution for different triplets is at random only rarely will a diploid and a haploid sister cell result.

A triploid Datura has been reported by Blakeslee, Belling, and Farnham. It arose from a tetraploid fertilized by a normal. The normal diploid type has 24 chromo-

somes (n=12) (Fig. 81a). The triploid has 36 chromosomes (Fig. 81b). The haploid group is composed of 1 extra large (L), 4 large (l), 3 large medium (M), 2 small medium (m), 1 small (S), and 1 extra small (s) chromosomes. The diploid group is therefore 2 (L+4l+3M+2m+1S+1s) and the triploid has three of each kind.

The maturation divisions have been studied by Belling and Blakeslee. The reduced groups consist of 12 sets of three each, united as in Fig. 81b. These trivalents have the same size relations as have the bivalents in the diploid group, *i.e.,* they are formed by the union of like chromosomes only, which are united in various ways as seen in the figures. Two may be united at both ends and the third joined on at one end only, etc.

At the first division two of each triplo-set pass to one pole and one to the other pole of the spindle (Fig. 75, third column), and since the assortment takes place at random in the different triplets several combinations of chromosomes are realized. The numbers found in one count of 84 pollen mother cells are recorded below in Table I. The results are in close agreement with the expectation for random assortment.

TABLE I

ASSORTMENT OF CHROMOSOMES IN 84 POLLEN MOTHER CELLS OF TRIPLOID DATURA, 19729(1)

Metaphase of Second Division.

Assortment of Chromosomes	12 + 24	13 + 23	14 + 22	15 + 21	16 + 20	17 + 19	18 + 18
Nos. of double groups	1	1	6	13	17	26	20
Calculated on random orientation of trivalents	0.04	0.5	2.7	9.0	20.3	32.5	19.0

Rarely the first division of the triploid may be omitted. This is favored by transient cold. At the second division

an equatorial division of the chromosomes takes place, giving two giant cells with 36 chromosomes each.

As a rule very few functional pollen grains are formed in the triploid, but apparently the egg-cells are more often functional. For instance, when a triploid is pollinated by a normal plant, the number of normal offspring (2n) produced is much beyond expectation on the assumption that the chromosomes of the egg are freely assorted.

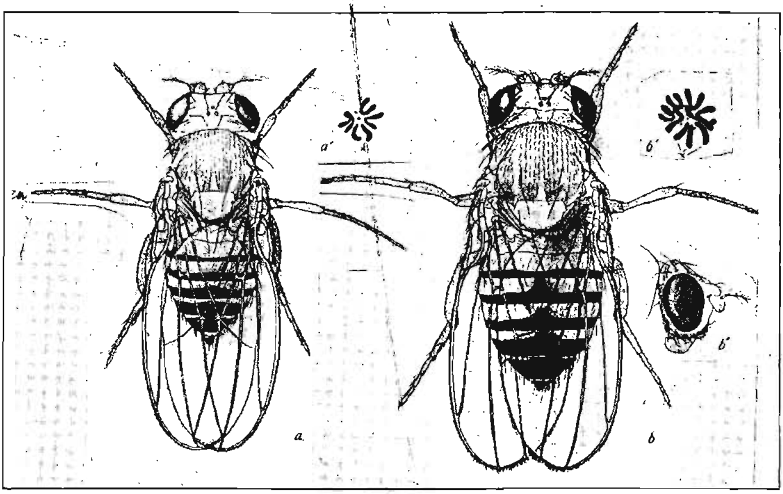


FIG. 82.
a, Normal or diploid female, and *b*, triploid of Drosophila melanogaster.

Triploid Drosophilas have been found by Bridges (Fig. 82). They are females because they have three X-chromosomes balanced against three of each kind of autosome. This is the same balance that produces the normal female. Since genetic factors in all the chromosomes are known, it has been possible to study the behavior of the

chromosomes at maturation by means of the character-distribution in the progeny. It has also been possible to study the crossing-over, and to determine that the chromosomes mate in threes.

In true triploid Drosophilas there are three sets of ordinary chromosomes and three X-chromosomes also. If, on the other hand, there are only two X-chromosomes present the individual is an intersex. If only one X is present the individual is a supermale. These relations are as follows:

3a+3X=triploid female
3a+2X=intersex
3a+1X=supermale

In bisexual animals another triploid is known in an embryonic stage. Females of the bivalens variety of the threadworm Ascaris have been reported whose ripe eggs with two chromosomes have been fertilized each by a spermatozoön of a univalens variety with one chromosome. These eggs produce embryos with three chromosomes in each cell. Since the embryos escape before their own germ-cells mature, the most significant feature of their chromosome behavior, namely, union during conjugation, has not been observed, for as yet no adult triploids of Ascaris have been reported.

Triploids have been produced by crossing diploid species and back-crossing the hybrid (that has diploid germ-cells owing to the failure of conjugation and reduction) to one of the parental stocks. The experiment was carried out by Federley with three species of moths with the following chromosome numbers.

	Diploid	*Haploid*
Pygaera anachoreta	60	30
Pygaera curtula	58	29
Pygaera pigra	46	23

The hybrid between the first two species has 59 chromosomes (30+29). When the germ-cells of the hybrid reaches the maturation stages no union takes place between the chromosomes. At the first maturation division, each of the 59 chromosomes splits into daughter halves. Each daughter cell receives this number. At the second maturation division many irregularities occur. The chromosomes split again, but the halves often fail to separate. Nevertheless, the male is partially fertile and, as the result shows, some of his germ-cells contain the full number (59) chromosomes. The F_1 female is sterile.

If the F_1 male is back-crossed to a female of one of the parent species, to anachoreta, for example, whose ripe eggs contain 30 chromosomes, the second hybrid has 89 chromosomes (59+30), and is therefore a hybrid triploid. These F_2 hybrids resemble closely the F_1 hybrids. They have two sets of anachoreta chromosomes and one set of curtula chromosomes. They are, in a sense, permanent hybrids, although in each generation only half of their chromosomes conjugate. For instance, in the ripening of the germ-cells of these 89 chromosome hybrids the double set of anachoreta chromosomes (30+30) conjugates, the 29 curtula chromosomes remain single. The former separate at the first division, the latter divide, giving 59 to each cell. At the second division all 59 chromosomes divide. The germ-cells contain, therefore, 59 chromosomes and are diploid. As long as back-crossing continues it should be possible to produce triploid individuals. While under controlled conditions it might be possible to maintain a triploid line in this way, it is not probable, owing to the sterility of the offspring resulting from irregularities in the spermatogenesis of the hybrid, that under natural conditions a permanent triploid race could be established.[1]

[1] The account in the text has been intentionally somewhat simplified. In

The embryonic development of triploid individuals is expected to be normal because of the balanced condition of the genes. The only inharmonious factor that may enter into the situation is the relation between three sets of chromosomes and the inherited quantity of cytoplasm. How far auto-regulation takes place is not definitely known, but it may be surmised that in plants at least the cells of the triploid are larger than those of the normal type.

Other triploid types that have arisen or have been produced by crossing wild species, one of which has twice as many chromosomes as the other, will be described in a later chapter.

the F_1 hybrid one or more of the chromosomes appear to conjugate at times. Probably reduction follows for this pair, which would change by one or more the actual number of chromosomes in the germ-cells of the F_2 individuals.

CHAPTER X

HAPLOIDS

THE genetic evidence indicates that one complete set of chromosomes at least is required for normal development. A cell with one set of chromosomes is said to be haploid, and an individual made up of such cells is sometimes called a haplont or frequently, by extension, a haploid. The embryological evidence also indicates that one set of chromosomes is necessary for development. It does not follow, however, that the diploid set can be replaced directly by a haploid set without serious consequences, so far as the developmental conditions are involved.

Eggs that have been incited to develop by artificial agents may develop into embryos whose cells have only one set of chromosomes. Not infrequently, however, the eggs double the number of the chromosomes (by suppressing a protoplasmic division) before they begin to develop, and these fare better than the haploids.

By cutting off a fragment from a sea urchin egg, and fertilizing it with a single sperm, an embryo can be obtained with only one set of chromosomes, the paternal set. By constricting the egg of triton immediately after fertilization, Spemann and later Baltzer have sometimes been able to separate a piece of the egg that contains only a single sperm-nucleus (Fig. 83), and one such embryo was carried through by Baltzer to the time of metamorphosis.

If frogs' eggs are exposed to X-rays, or to radium for a sufficient time to injure or to destroy the chromosomes,

and if, as Oscar and Gunther Hertwig have shown, these eggs are then fertilized, they may produce embryos whose cells have the half number of chromosomes. Conversely, if the spermatozoa of the frog are radiated they may enter the eggs, but may fail to take further part in the development. Under these circumstances the egg may develop, for a time, with a haploid set derived from the egg nucleus. In some of these eggs, on the other hand,

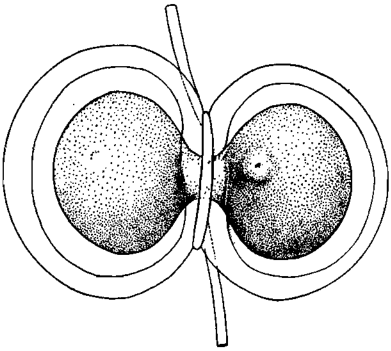


FIG. 83.

Egg of Triton constricted in two, immediately after fertilization. In the right half the polar body is shown. (After Spemann.)

the chromosomes of the egg may first divide without the protoplasm dividing, and in this way the full number of chromosomes is restored before development begins. These eggs produce embryos that develop into normal tadpoles.

Most of the artificial haploid forms obtained in these various ways are weak. They die, in most cases, long before the adult stages are reached. It is not evident why this should be true, but there are several possibilities that may be taken into account. If a whole egg with a haploid nucleus is incited by artificial means to parthenogenetic development, and if, before differentiation sets

in, it divides the same number of times as does the normal egg, each of its cells will be in proportion to its chromosome number twice as large as the normal cells in proportion to their chromosome number. In so far as the development of the cell is dependent on its genes there may be an insufficiency of gene material to produce a normal effect on a cytoplasm of double volume.

On the other hand, if such an egg should pass through one more division than does the normal egg before differentiation (organ formation) begins, the number of chromosomes (the nuclear size) would then be proportionate to the cell size—there would be twice as many cells, and twice as many nuclei in the whole embryo as in the normal. The embryo as a whole would then contain the same total number of chromosomes as does the normal embryo. How far the smaller size of the cells in such a case might affect the developmental process we do not know at present. Observation of the cell-size of haplonts seems to show that the cells have the normal size and that the nuclei are only half as large as the normal ones. It appears, then, that the embryo does not rectify its nuclear cytoplasmic relation as just indicated.

It might be possible in another way to determine whether the weakness of the artificial haplonts is due to an insufficiency of genes for cells as large as normal ones. Half of an egg, containing a single sperm nucleus, would, if it passed through the number of divisions characteristic of the normal egg, be made up of cells and nuclei having the normal size-ratio to each other. Sea urchin embryos of this kind have, in fact, long been known. They become plutei that appear to be normal, but none have been carried beyond the pluteus stage because, for one reason, it is difficult to carry even normal embryos further than this stage under artificial conditions. It is not certain, therefore, whether these haplonts are as viable

as normal embryos. Boveri and others have studied extensively fragments of sea urchins' eggs, most of which were probably smaller than half an egg. Boveri concluded that these haplonts die, for the most part, before the gastrulation stages or soon thereafter. It is possible that these "fragments" never entirely recover from the operation, or that they do not contain all the essential constituents of the cytoplasm.

A comparison of these embryos with those obtained by isolating blastomeres of normal diploid eggs has certain points of interest. It is possible by means of calcium-free sea water to isolate the first two, or the first four, or the first eight blastomeres of the segmenting egg of the sea urchin. *Here there is no operative injury, and each cell* has the double number of chromosomes. Nevertheless, many of the ½ blastomeres develop abnormally, fewer still of the ¼ blastomeres produce plutei, and probably none of the ⅛ blastomeres pass beyond the gastrula stage. This evidence shows that, aside from the number of chromosomes and from the nucleo-plasma ratio, small size in itself has a deleterious influence. What this may mean is not known, but the surface relations to the volume vary with the size and may possibly enter into the result.

These experiments do not hold out much promise of obtaining normal vigorous haplonts by diminishing artificially the amount of the protoplasm of the eggs in species already adjusted to the diploid condition. Nevertheless, under natural conditions there are several cases known where haplonts exist, and there is one case recorded where a haplont of a diploid species has reached maturity.

Blakeslee discovered a plant, in his cultures of Datura, that was haploid, Fig. 84. With care it was kept alive and by grafting upon diploid plants it has been maintained

for several years. This plant resembles, in all essential respects, the normal plant, except that it produces a very small number of haploid pollen grains. These pollen

FIG. 84.
A haploid plant of Datura. (After Blakeslee, in Journal of Heredity.)

grains are the ones that have received one set of chromosomes after a rather devastating attempt to pass through the maturation stages.

Two haploid tobacco plants have been reported by Clausen and Mann (1924) that appeared in a cross between *Nicotiana Tabacum* and *N. sylvestris*. Each had 24

chromosomes, which is the haploid number of the Tabacum species. One of these haplonts was "a reduced replica" of the "variety" of the Tabacum parent, but the expression of the characters was somewhat exaggerated.

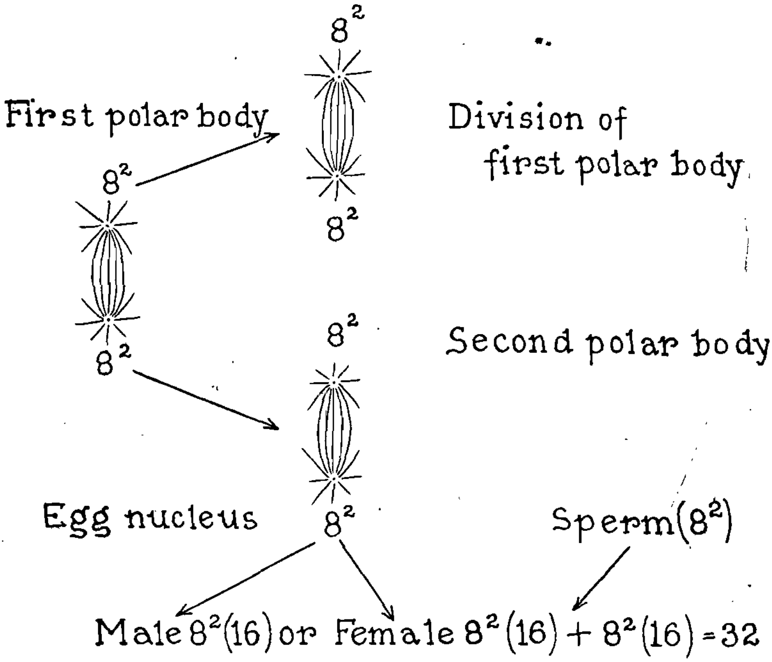


FIG. 85.

Diagram illustrating the two maturation divisions of the egg of the honey bee. The fertilization of the egg by the sperm is indicated in the lower part of the diagram with a subsequent doubling of the chromosomes by breaking into two parts.

It was about three-fourths the height of the parent type; the leaves were smaller, the branches more slender, and the flowers distinctly smaller. It was less vigorous than the parent type; it bloomed profusely but produced no seeds. Its pollen was completely defective. The other haplont showed similar relations to the variety of Tabacum

from which it was derived. The first maturation of the pollen mother cells of these haplonts was irregular, few or many of the chromosomes passing to the poles, the rest remaining at the equator of the spindle. The second maturation division was somewhat more regular, but lagging chromosomes failed to reach either pole.

Nature seems to have been successful in producing a few haplonts in species in which one sex is diploid. Male bees, wasps, and ants are haplonts. The eggs of the queen bee contain 16 chromosomes, which become 8 bivalents after conjugation (Fig. 85). Two maturation divisions take place, reducing the number to 8 chromosomes. If an egg is fertilized it produces a female (queen or worker) with the diploid number of chromosomes, but if an egg is not fertilized it develops parthenogenetically with the half number of chromosomes.

An examination of the nuclear and cell-size of the different tissues of the female and male bees (Boveri, Mehling, Nachtsheim) has shown that, in general, there is no constant difference between the diplont and the haplont. There is, however, a peculiar condition in the early embryonic stages both of the female and male bee that has somewhat complicated the situation. In the cells of the embryo of the female, the chromosomes become twice as numerous as at first, apparently by each chromosome *separating* into two parts. In the cells of the embryo of the male, the same process occurs, and is there repeated even a second time, so that there appear to be 32 chromosomes present. The evidence seems to indicate that the chromosomes do not actually increase in number but "fragment." If this is the correct interpretation there is no increase in the number of the genes. The female has still twice the number of those in the male. What relation, if any, this fragmentation may have to nuclear size is not clear at present.

In the germ-track of the male and female the fragmentation does not seem to take place, or if it does the pieces rejoin before the maturation stage.

The best evidence that the male bee is a haplont, or at least that its germ-cells are haploid, is found in the behavior of the cells at the maturation divisions. The first division is abortive (Fig. 86, a, b). An imperfect spindle forms in connection with 8 chromosomes. A piece of the protoplasm constricts off without chromatin. A second spindle develops and the chromosomes divide (Fig. 86, d-g), presumably by splitting lengthwise, and the daugh-

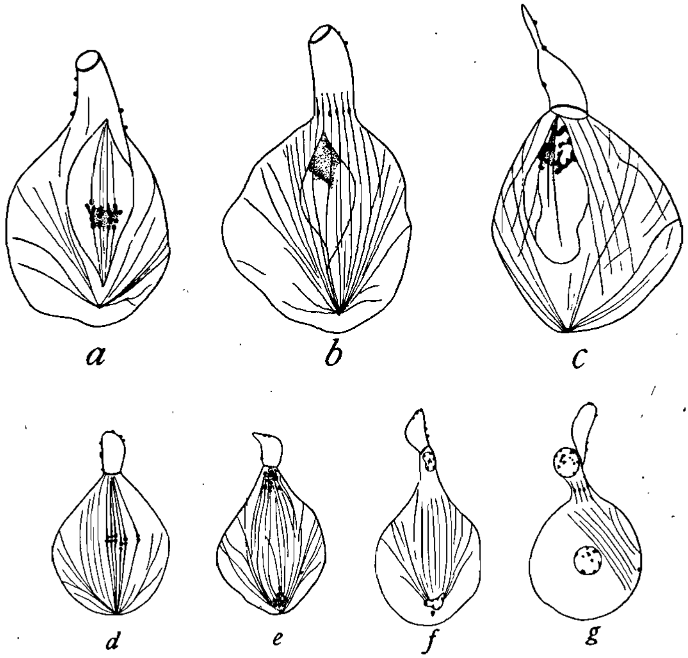


FIG. 86.

The two maturation divisions of the germ-cells of the male of the honey bee. (After Meves.)

ter halves pass to the poles. A small cell cuts off from a large one. The latter becomes the functional sperm. It has the haploid number of chromosomes.

The male rotifer, Hydatina senta, is said to be haploid (Fig. 87c), and the females diploid. Under unfavor-

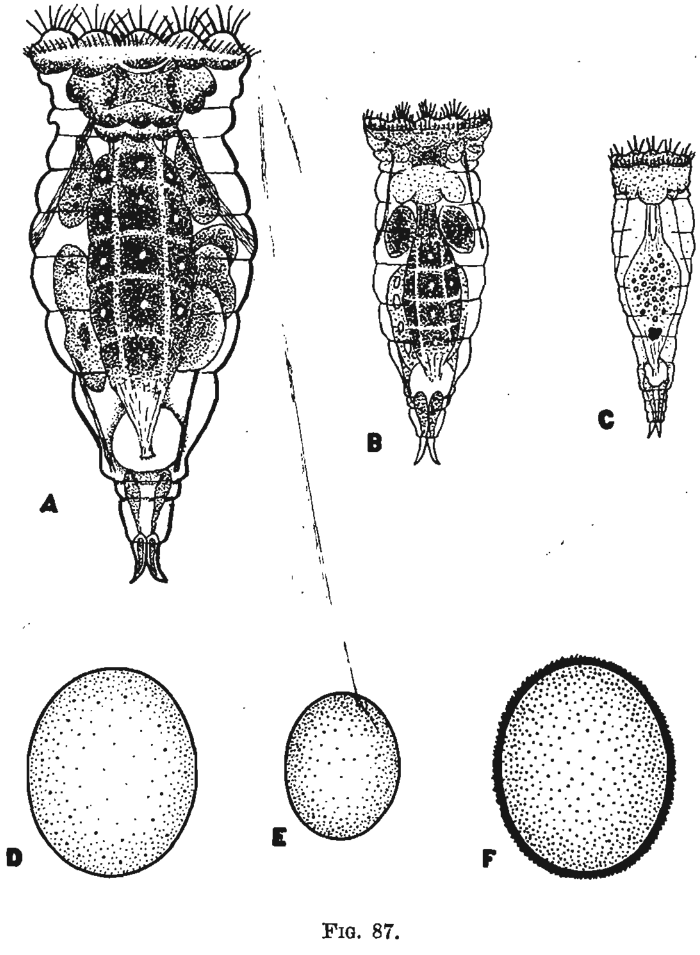


FIG. 87.

A, parthenogenetic female of Hydatina senta; B, young female of same; C, male of same; D, parthenogenetic egg; E, male-producing egg; F, winter egg. (After Whitney.)

able conditions of food, or when fed on the protozoön Polytoma, only female rotifers occur. Each female is diploid, and her eggs are at first diploid. Each egg gives off only one polar body—each chromosome splitting into like halves. The full number of chromosomes is retained in the egg that develops by parthenogenesis into a female. When fed on other food (Euglena, for example), a new type of female appears. If she is fertilized by a male at the moment she emerges from the egg, she produces sexual eggs only, which give off two polar bodies and retain the haploid number of chromosomes. The sperm nucleus, already within the egg, unites with the egg nucleus to form a diploid female that starts once more a parthenogenetic line. If, however, the special type of female, just described, is not fertilized, she produces smaller eggs which give off two polar bodies and probably retain the half number of chromosomes. They develop by parthenogenesis into male haplonts. The male is sexually mature a few hours after birth; he never grows any larger and dies after a few days.

The males of the white "fly," Trialeurodes vaporariorum, have been shown by Schrader to be haplonts. It had been discovered by A. W. Morrill that, in America, virgin females of this fly give rise to male offspring only, and Morrill and Back found this in another member of the same family. On the other hand, in England, virgin females of the same white fly give rise to females only, according to Hargreaves and later to Williams. Schrader (1920) studied the chromosomes in the American form. There are 22 chromosomes in the female and 11 in the male. The mature eggs have 11 bivalent chromosomes. Two polar bodies are given off, leaving 11 single chromosomes in the egg. If the egg is fertilized 11 chromosomes are added by the sperm nucleus. If the egg is not fertilized it develops by parthenogenesis with 11 chromosomes

present in all cells of the embryo. In the maturation stages of the germ-cells of the male, there is no evidence of a reduction division (not even a rudimentary process as in the bee) and the equational division does not differ from the spermatogonial divisions.

There is some evidence that the unfertilized eggs of lice develop into males, as suggested by the breeding experiments of Hindle. In one of the mites, Tetranychus bimaculatus, the unfertilized eggs produce males, the fertilized eggs, females (according to several observers). It has been shown by Schrader (1923) that the males are haplonts with only three chromosomes, the females are diplonts with six chromosomes. The early ovarian eggs have six chromosomes that conjugate to give three bivalents. Two polar bodies are given off, leaving three chromosomes in the egg. If the egg is fertilized three chromosomes are added, giving six in the female, if the egg is not fertilized it develops directly into a male with three chromosomes in each cell.

Virgin females of one species of thrips, Anthothrips verbasci, examined by A. F. Shull, produce only males from unfertilized eggs. These males are probably haplonts.

In mosses and liverworts the protonema and moss plant stage (gametophyte) are haplonts. Wettstein has by artificial means brought about the doubling of the number of chromosomes in cells of the protonema and from these has obtained diploid protonema and moss plants. This result proves that the difference between this stage and the sporophyte stage is not due to the number of chromosomes that each contains but is a developmental phenomenon in the sense that in order to reach the sporophyte stage the spore must pass through the gametophyte condition.

CHAPTER XI

POLYPLOID SERIES

IN recent years an ever increasing number of closely related wild and of cultivated types have been reported whose chromosome numbers are multiples of a basal haploid number. The polyploid series run in groups which suggest that members of the series with the higher numbers have come from the lower members by a continuous process of additions. Whether taxonomists will decide to give such forms as are stable specific rank is for them to decide.

It is probably significant that the polyploid series have been found in several groups that were known as polymorphic groups that had bewildered taxonomists owing to their variability and to their close resemblance to each other, to their failure in many cases to breed true from seeds, etc. All this accords with the cytological findings. In so far as the chromosome groups are balanced, the genetic expectation is that these plants would be very similar, except in so far as the increase in the size of the cells may introduce physical factors that affect the structure of the plant, and except in so far as the increased number of the genes may introduce chemical effects in the cytoplasm.

The Polyploid Wheats.

In the small grains, wheat, oats, rye, and barley, multiple chromosome groups have been found. The wheat series has been most extensively studied and the hybrid types produced by crossing them have been examined in a

number of cases. Of these, T. monococcum, has the fewest chromosomes, *viz.*, 14 (n=7). It belongs to the Einkorn group and can be traced back, according to Percival

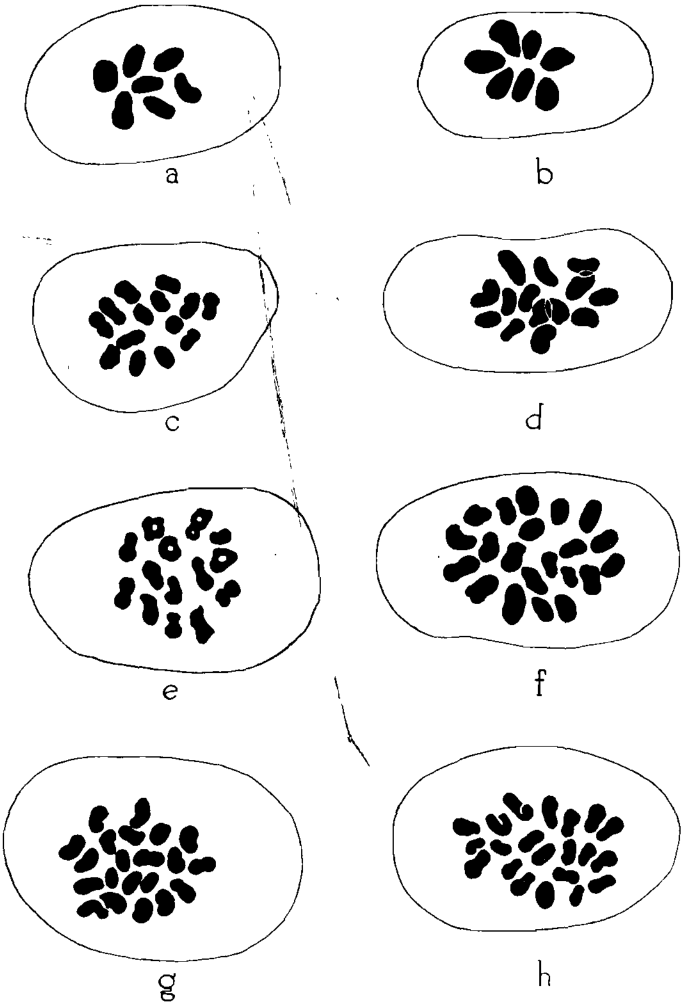


FIG. 88.

Reduced number of chromosomes of diploid, tetraploid, and hexaploid wheats. (After Kihara.)

(1921), to the Neolithic period in Europe. Another type, the Emmer group, with 28 chromosomes, was grown in Europe in prehistoric times, and in Egypt as early as 5400 B.C. It was later supplanted in the Graeco Roman period by wheat with 28 chromosomes, and by one with 42 chromosomes of the Vulgare group (Fig. 88). The number of varieties is greatest in the Emmer group, but there are more different "forms" in the Vulgare group.

The chromosomes have been studied by several investigators. The most recent work is that of Sakamura (1920) and Kihara (1919, 1924) and Sax (1922). The following account is taken largely from Kihara's monograph and to some extent also from Sax's papers. The next table gives the observed diploid number of chromosomes and the observed or estimated haploid number.

	Haploid	*Diploid*
Einkorn group, Triticum monococcum	7	14
Emmer group, Triticum dicoccum	14	28
Emmer group, Triticum polonicum	14	28
Emmer group, Triticum durum	14	28
Emmer group, Triticum turgidum	14	28
Vulgare group, Triticum Spelta	21	42
Vulgare group, Triticum compactum	21	42
Vulgare group, Triticum vulgare	21	42

The haploid groups are represented in Fig. 88a (monococcum), Fig. 88e (durum), and Fig. 88h (vulgare).

The normal maturation of a member of each of these groups is shown in Fig. 89 from Sax. In the Einkorn wheat the seven gemini (conjugated chromosomes) divide at the first division, seven going to each pole. There are no lagging chromosomes. At the second division of each daughter cell the seven chromosomes split into daughter halves. Seven go to each pole. In the Emmer type the 14 gemini divide at the first maturation stage. Fourteen chromosomes go to each pole. At the second division each

chromosome splits, and 14 daughter chromosomes move to each pole. In the Vulgare type the 21 gemini divide at the first maturation division. Twenty-one go to each pole. At the second division the daughter halves split and 21 move to each pole.

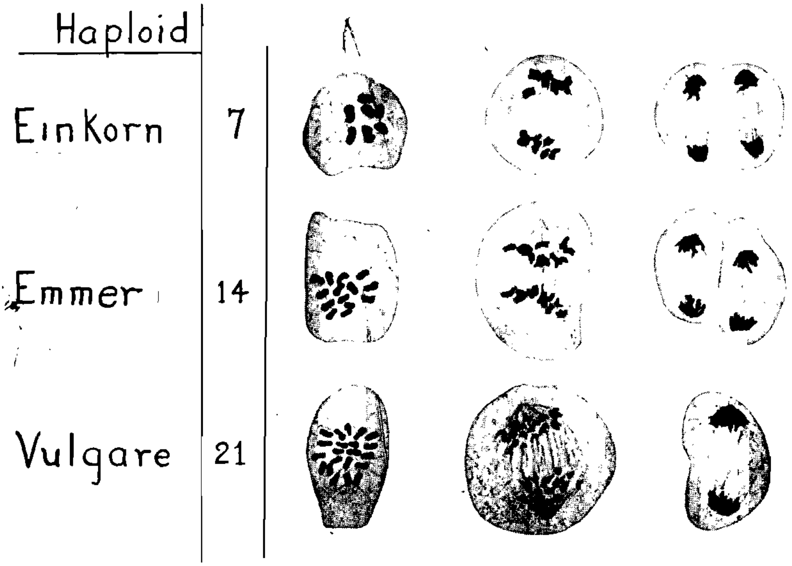


FIG. 89.
The first, or reduction, division of diploid, tetraploid, and hexaploid wheats. (After Sax.)

This series of types may be interpreted as diploid, tetraploid, and hexaploid. Each is balanced and each is stable.

Crosses have been made between several of these types with different chromosome numbers. Some of the combinations produce slightly fertile hybrids, others completely sterile ones. The behavior of the chromosomes in several of the combinations, where different parental

numbers are involved, brings out some interesting relations. A few examples will serve as illustrations.

Kihara examined the hybrid produced by crosses between an Emmer with 28 chromosomes (n=14) and a Vulgare type with 42 chromosomes (n=21). The hybrid

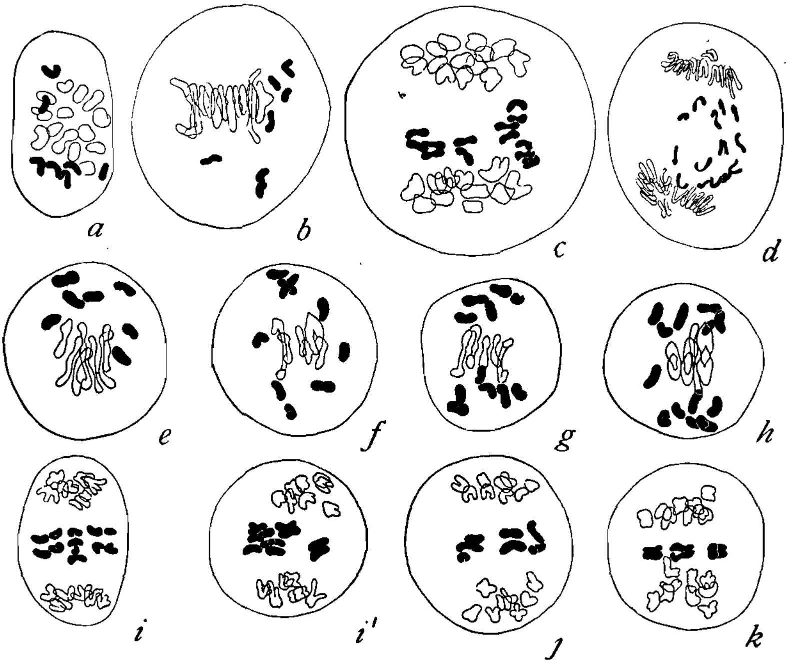


FIG. 90.
Reduction division of hybrid wheats. (After Kihara.)

has 35 chromosomes. It is therefore a pentaploid hybrid. In the maturation stages (Fig. 90a-d) there are 14 gemini and 7 single chromosomes. The former divide, 14 going to each pole; the latter, the single chromosomes, are irregularly scattered on the spindle, where they lag for some time after the "reduced" chromosomes have reached the poles (Fig. 90d). Later these single chromo-

somes split lengthwise, and the daughter chromosomes move to the poles, not, however, with complete regularity. When the distribution is equal there will be 21 chromosomes at each pole.

EMMER BY VULGARE

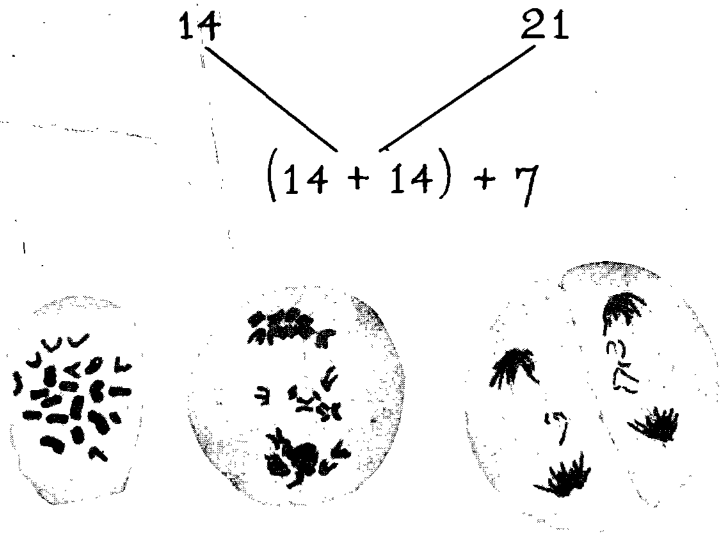


FIG. 91.
Reduction division of the hybrid between Emmer and Vulgare wheat. (After Sax.)

In passing it should be recorded that according to Sax's results for triploid wheat, the 7 single chromosomes do not divide at this time, but are distributed unequally to the poles, the more common distribution being 3 and 4 (Fig. 91).

At the second division, according to Kihara, 14 chromosomes that are split lengthwise appear and 7 chromosomes that are not split. The former divide, 14 going to

each pole, while the 7 singles are distributed at random—more often 3 going to one pole and 4 to the other. According to Sax, the 7 single as well as the 14 reduced chromosomes split at the second division.

Whichever interpretation holds for the single chromosomes (and there are in other forms precedents for either interpretation), one important fact is evident, *viz.*, that conjugation takes place only between 14 chromosomes. Whether this union is between the 14 chromosomes derived from the Emmer and 14 chromosomes derived from the Vulgare, or whether the 14 chromosomes of the Emmer unite to make 7 conjugants and 14 of the Vulgare unite to make 7 conjugants, leaving one set of 7 over, is not clear from the cytological evidence. A genetic study of these or similar combinations (this one gives a fertile hybrid) may furnish decisive evidence, but this is lacking at present.

Kihara also crossed Einkorn, having 14 chromosomes (n=7), with Emmer wheat, having 28 chromosomes (n=14). The hybrid, having 21 chromosomes, is a triploid. In the maturation of the germ-cells of the hybrid (pollen mother cells) there is much more irregularity than in the last case (Fig. 90e-k). The number of the conjugating chromosomes is variable and their union, when it occurs, is less complete. The number of the gemini varies as shown in the next table.

Somatic number	*Gemini*	*Singles*
21	7	7 (Fig. 90e)
21	6	9 (Fig. 90b)
21	5	11 (Fig. 90g)
21	4	13 (Fig. 90h)

At the first division the components of the gemini separate and pass to the poles. The splitting of the single chromosomes does not always take place before they have

moved to one or the other pole; some reach the poles undivided, others split and the halves move to the poles. Not infrequently 7 single chromosomes are left in the middle plane between the two polar groups (Fig. 90i). Three counts are given in the following table:

Upper pole	*Between the poles*	*Lower pole*
8	6	7 (Fig. 90i)
9	4	8 (Fig. 90j)
9	3	9 (Fig. 90k)

At the second division 11 or 12 chromosomes are, as a rule, present; some are doubles (split lengthwise), others singles. The former divide normally, the daughter chromosomes going to one or the other pole; the singles are distributed without division to one or the other pole.

From this evidence it is not possible to determine which chromosomes conjugate in the hybrids. Since the number of gemini does not exceed 7, these may be interpreted as the result of union of the 14 chromosomes of the Emmer parent, or as the result of the union of 7 of the Einkorn with 7 of the Emmer chromosomes.

In a few crosses between Emmer and Vulgare, fertile hybrids have been obtained. Kihara has studied the chromosomes in the maturation division of some of the F_3, F_4, and later generations. The chromosome numbers in the plants vary and there are irregularities in the distribution of some of them during maturation, leading to further irregularities, or to the reëstablishment of a stable type like one of the original types, etc. These results, important for the genetic study of the hybrids, are too complex for our present purpose.

Kihara studied hybrids (one combination) between a Vulgare wheat and a race of rye, the former having 42 chromosomes (n=21), the latter 14 chromosomes (n=7). The hybrid (with 28 chromosomes) may be called a

tetraploid. This hybrid between these two widely different species is, according to earlier observations, sterile, but fertile according to other observers.

In the maturation stages of the germ-cells, few or even no conjugating chromosomes were observed, as shown in the next table:

Gemini	*Singles*
0	28
1	26
2	24
3	22

The distribution of the chromosomes to the poles is very irregular; few if any of the singles divide before reaching the poles; some of them are left scattered in the cell. In the second division many of the chromosomes split, but those that divided in the first division lag and pass slowly to the pole; the number that lag is, however, much less than in the first division.

The almost complete absence of conjugating chromosomes in the cross between wheat and rye is the most interesting feature of the cross. The resulting irregularity in the distribution of the chromosomes will probably account for the generally observed sterility of the hybrid. There is a possibility that all the chromosomes (or most of them) belonging to one species might, as a rare event, pass to one pole. This might lead to the formation of a functional pollen grain.

The Polyploid Roses.

Since the time of Linnaeus the classification of many of the roses has baffled the skill of taxonomists. The recent discoveries of a Swedish botanist, Täckholm, and of three English botanists, Harrison and Blackburn in collaboration, and Hurst, a rose expert and geneticist,

have shown that certain groups of roses, especially those belonging to the family of canina rose, are polyploid types. Their differences are not only due to polyploidy, but combined with this there is evidence of extensive hybridization.

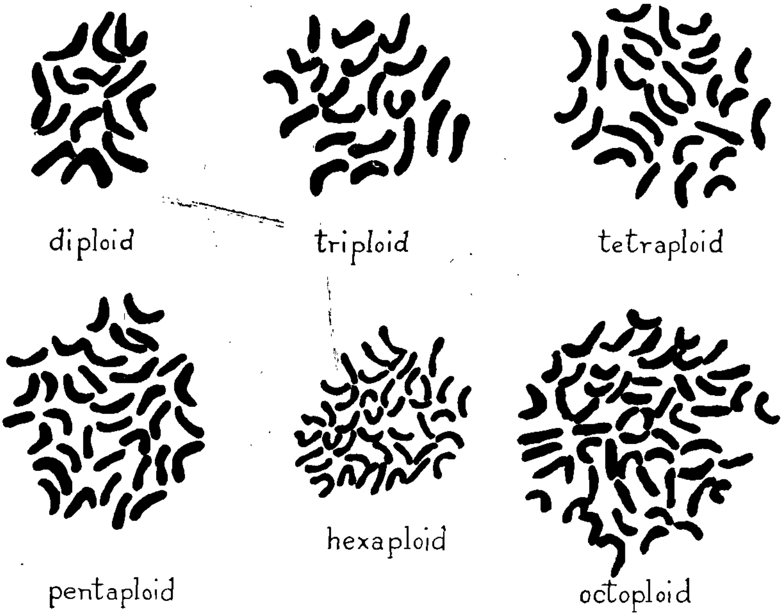


FIG. 92.
Polyploid series of roses. (After Täckholm.)

Täckholm has recently made an elaborate study of these roses. His account may first be followed. The species with 14 chromosomes (n=7) have the smallest number, and may be taken as the basal type. There are triploids (3 times 7), tetraploids with 28 chromosomes (4 times 7), pentaploids (5 times 7), hexaploids with 42 (6 times 7), and octoploids with 56 (8 times 7). See Fig. 92. In the maturation division of some of these polyploids

that are balanced, all the chromosomes are united in pairs (gemini), while in those polyploids with odd numbers and even in some of those with even numbers (taken to be hybrids) only 7 (or 14) gemini are present, the rest of the chromosomes being single in the first maturation division. In other words, when there are four, six, or eight chromosomes of each of seven kinds they conjugate in twos, as though these types were diploid. Whatever their origin may have been, the chromosomes never conjugate in fours, sixes, or eights. In these polyploids, the conjugants separate at the first maturation division, half going to each pole. At the second division each chromosome divides, and half of each goes to one or the other pole. The germ-cells, whether pollen or ovules, thus come to contain half the original number of chromosomes. Hence, if they propagate sexually, the characteristic number is maintained.

Another group of roses is regarded as hybrid by Täckholm, because the changes that take place in their germ-cells show them to be unstable forms. Some of these have 21 chromosomes, hence are triploids. In the early maturation stages of the pollen mother cells there are 7 bivalents (gemini) and 7 single chromosomes. At the first division the 7 bivalents divide and 7 go to each pole; the 7 single chromosomes do not divide and are distributed at random to the poles. Hence several combinations are possible. The type is unstable in this respect. At the second maturation division, all the single chromosomes divide, whether they come from the earlier bivalents or from single chromosomes. Many of the resulting cells degenerate.

In other hybrids there are 28 chromosomes (4 times 7), but these are not classified as true tetraploids by Täckholm, because the behavior of the chromosomes at the time of conjugation indicates that there are not four of

each kind. Only 7 bivalents appear and 14 single chromosomes. At the first division the 7 bivalents split, the 14 singles do not divide and are distributed irregularly.

In other hybrids there are 35 chromosomes (7 times 5). At maturation there are 7 bivalents and 21 single chromosomes (Fig. 93). Both behave as in the last case.

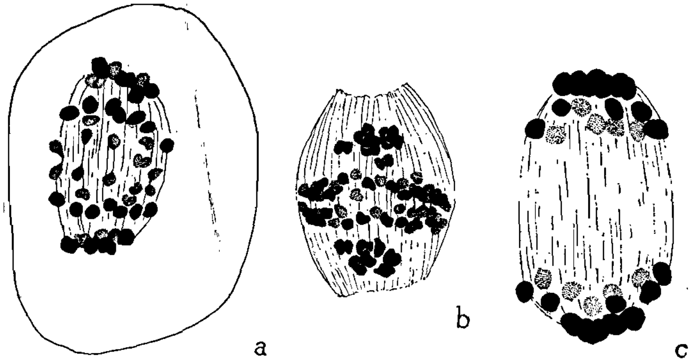


FIG. 93.

First maturation division of a thirty-five chromosome heterotypic rose. (After Täckholm.)

In a fourth type of hybrid there are 42 chromosomes (7 times 6). At maturation there are again only 7 bivalents, and, here, 28 single chromosomes. The behavior of the chromosomes at maturation is the same as before.

These four types of "hybrid roses" are classified below in tabular form in regard to their pollen formation.

7 bivalent and 7 single chromosomes. Whole number 21
7 bivalent and 14 single chromosomes. Whole number 28
7 bivalent and 21 single chromosomes. Whole number 35
7 bivalent and 28 single chromosomes. Whole number 42

The unique behavior of these hybrids consists in the conjugation of only 14 chromosomes to give the 7 bivalents. These chromosomes, we must suppose, are identi-

cal, or so nearly alike that they conjugate. It is not obvious why the other sets do not conjugate, unless, as Täckholm suggests, each set of 7 has come from a different wild species by crossing. The additional chromosomes arising in this way are sufficiently different from the original set and from each other to interfere with conjugation.

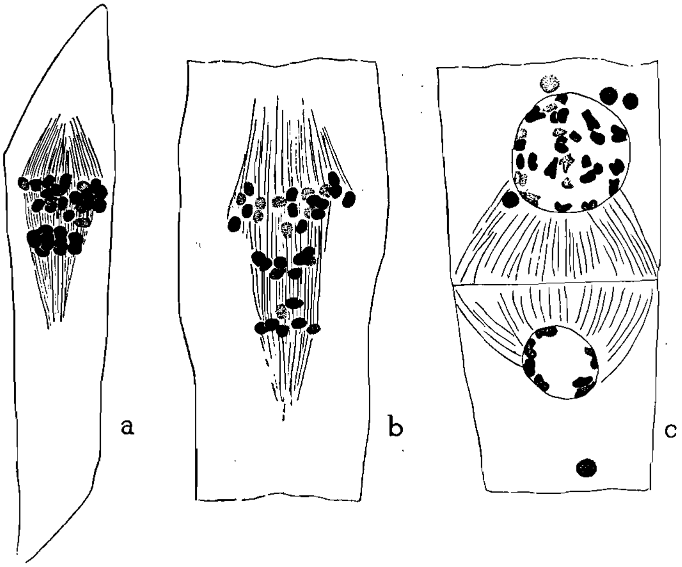


FIG. 94.

Maturation division of egg-cell of rose. All the single chromosomes move to one pole where they are joined by half of the conjugants. (After Täckholm.)

Two other hybrid forms may be mentioned; in both there are 14 bivalents and 7 single chromosomes. In these there are twice as many conjugating chromosomes as in the former hybrids.

In only a few hybrids of the canina group is the history of the chromosomes in the embryo mother sac (where the egg develops) described (Fig. 94). There are 7 bivalents

lying in the equator of the spindle, while all the single chromosomes are collected at one pole. The bivalents separate, half of each going to one pole, half to the other. One of the resulting daughter nuclei contains 7 chromosomes (derived from the bivalents) and all of the 21 single chromosomes, while its sister cell contains only 7 chromosomes. The egg-cell is derived from the former group. If the egg develops, as appears to be the case, from the (7+21)-chromosome cell, and is fertilized by a sperm with 7 chromosomes (the other pollen grains assumed to be non-functional), the fertilized egg will contain 35 chromosomes, the original number of such a type.

The reproductive processes in these polyploid hybrid roses has not been fully worked out. In so far as they reproduce by stolons they will maintain whatever number of chromosomes may result from fertilization. Those that form seeds by parthenogenesis may also maintain a definite somatic number. It seems probable that, as a result of the irregularities in the formation of the pollen and egg-cells many different combinations may be established. Without a knowledge of the chromosome interrelations of these types the hereditary processes would have been very baffling. Even with this advance in our knowledge there still remains a great deal to make clear the composition of these hybrid roses.

Hurst, who has studied species of Rosa, both wild and cultivated, thinks that the wild diploid species consist of five primary groups that may be designated AA, BB, CC, DD, EE, Fig. 95, a-d, e-h, i-l, m-p, q-t. Many combinations of these five fundamental types are recognizable. Thus, one tetraploid is designated BB, CC; another, BB, DD; one hexaploid is AA, DD, EE; another hexaploid is AA, BB, EE; an octoploid is BB, CC, DD, EE.

Hurst states that each member of the five primary series has at least 50 diagnostic characters. These can be

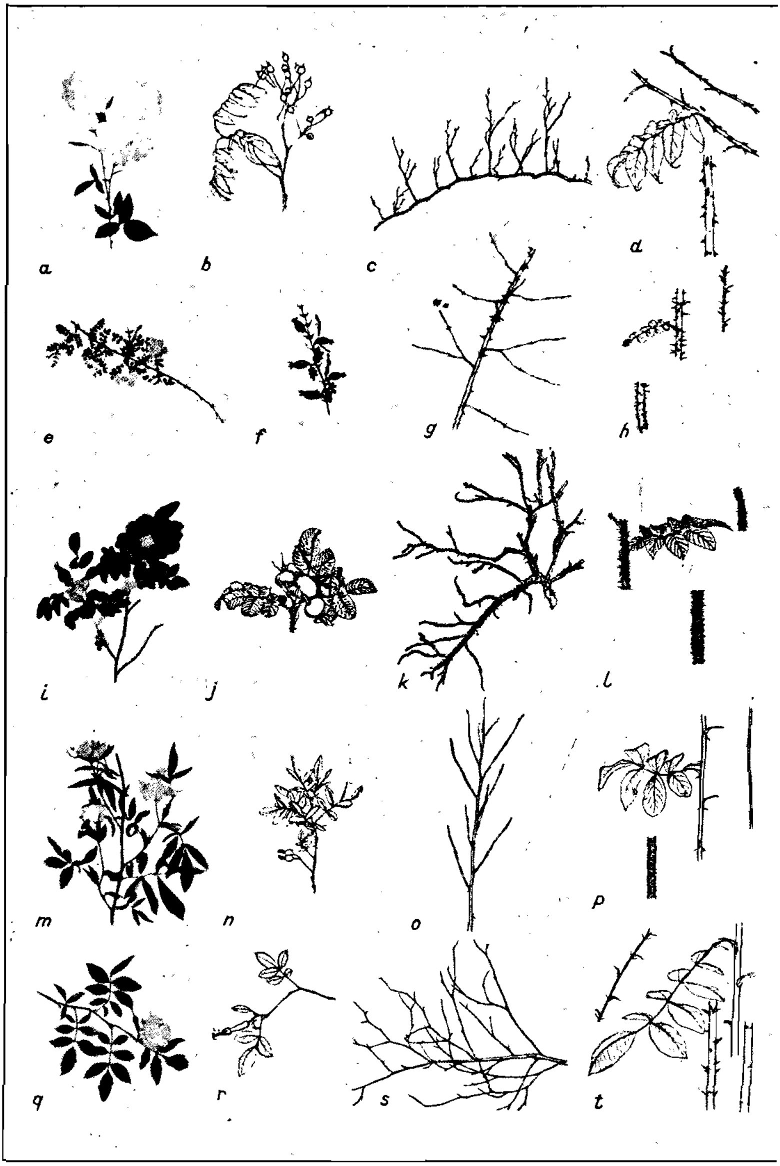


FIG. 95.

The five types of canina roses, *viz.*, a-d, e-h, i-l, m-p, q-t. The characteristics of each type are indicated in the same horizontal line including flower, seed capsule, method of branching, spines, and leaf insertion. (After Hurst.)

recognized in combinations in the hybrids. The environmental conditions may alternately favor the expression of one or the other set of characters. Hurst believes that a classification of the species of the genus is possible on the basis of these interrelations.

Other Polyploid Series.

In addition to the types that have just been described, there are a number of other groups in which multiple chromosome varieties and species have been reported.

The genus Hieracium is known to contain some species that reproduce by sexual methods, and other species that reproduce by parthenogenesis, even although stamens are sometimes present in them that may contain some normal pollen grains. Rosenberg has studied the development of the pollen of several species that produce pollen. He has also examined hybrids between different species. In the latter he has studied the maturation divisions of the pollen cells of the hybrid between H. auricula with 18 chromosomes (n=9) and H. aurantiacum with 36 (n=18). In the hybrid there are 9 gemini and 9 single chromosomes in the first maturation division but some exceptional cases are found, due perhaps to aberrant numbers of chromosomes in the pollen of one of the parents, *viz.*, H. aurantiacum. At the first division the gemini separate, and most of the single chromosomes divide.

Rosenberg has also studied the maturation division of F_1 hybrids between two tetraploid or 36 chromosome types, *viz.*, H. pilosella and H. aurantiacum. The somatic cells of the hybrid have 38 to 40 chromosomes. In two cases 18 gemini were present and 4 single chromosomes. In another cross between H. excellens, with 36 or 42 chromosomes (n=21), and H. aurantiacum, with 36 (n=18), there were in one case 18 gemini. It is probable that the H. excellens parent had 36 chromosomes. In another

similar cross, in which the pollen in F_1 was largely abortive, there were large numbers of gemini present and many single chromosomes. Results similar to these were

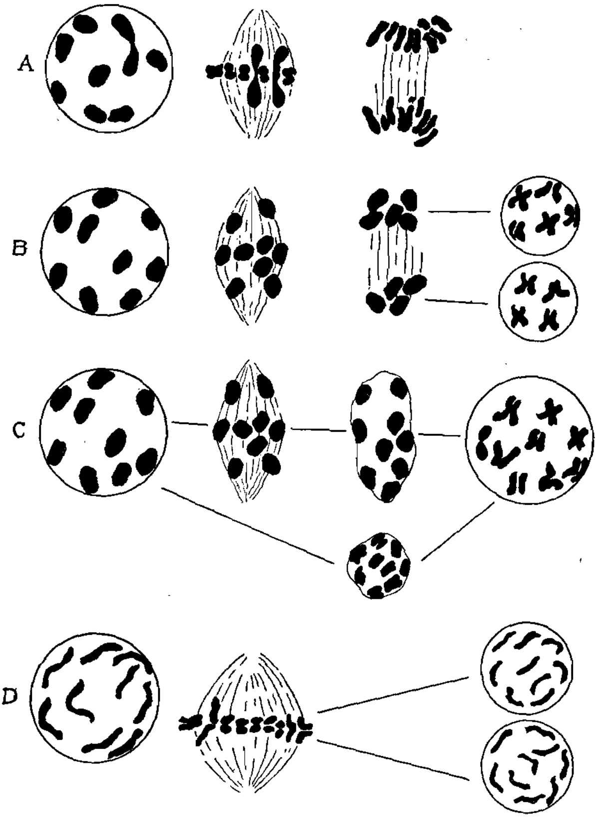


FIG. 96.

Maturation stages of several types of apogamous species of Hieracium. (After Rosenberg.)

found in two other tetraploid crosses. In general, the result with tetraploids shows that like chromosomes are present in these different species that conjugate with each other, or at least it seems more probable that the

gemini are formed in this way rather than that they are formed by the union of the like chromosomes within each species group.

Rosenberg has also studied the maturation of the pollen in species of Archieracium, in which species both sexual and parthenogenetic methods of reproduction occur, the latter being the more common method. There is no reduction division in the parthenogenetic types in

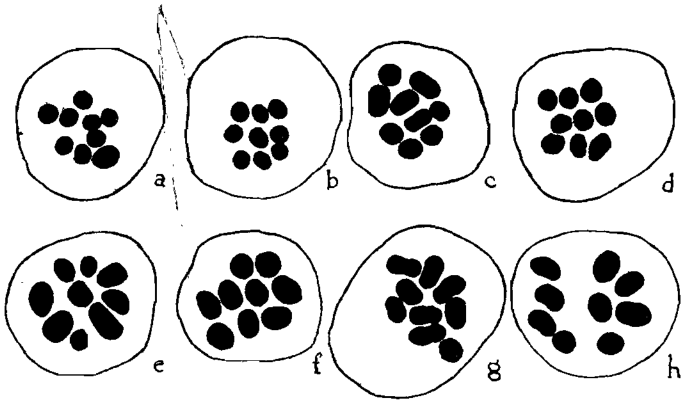


FIG. 97.

Types of chromosomes of eight varieties of chrysanthemums, each having the reduced number of nine chromosomes. (After Tahara.)

the embryo sac, but the diploid number of chromosomes is retained. The pollen development is much altered and good pollen is seldom present. The reduction divisions in the pollen mother cells are very irregular. Rosenberg has described the maturation stages of several apogamous species of Hieracium in which the pollen is scarcely ever functional (Fig. 96). He interprets the changes as, in part, due to their tetraploid origin (bivalent and single chromosomes appear in most types) and in part due to a progressive loss of all conjugation between the chromosomes, accompanied by a suppression of one of the matu-

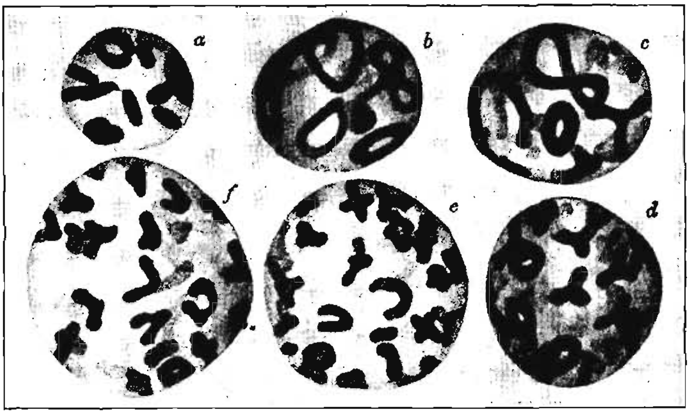


Fig. 98.

Multiple chromosome groups of different varieties of chrysanthemums; *a*, with 9; *b*, with 9; *c*, with 18; *d*, with 21; *e*, with 36; *f*, with 45 chromosomes. (After Tahara.)

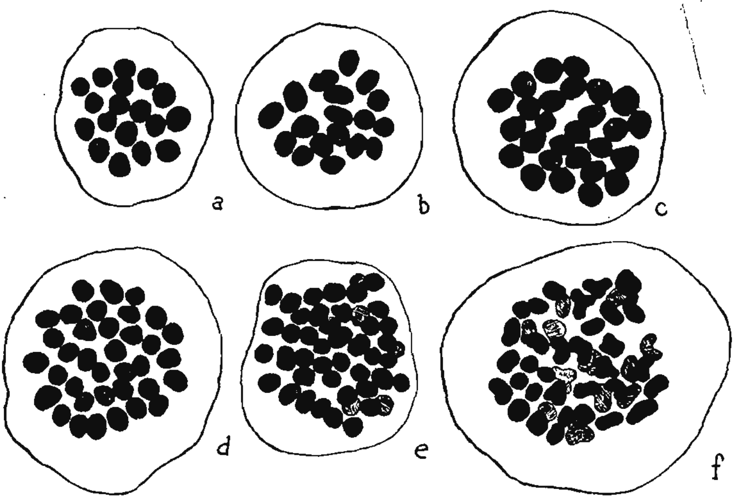


Fig. 99.

Nuclei in the diakinetic stage of several varieties of chrysanthemums, *a* and *b* with 18 chromosomes; *c* with 27; *d* with 36; *e* with 45; *f* with 45 chromosomes. (After Tahara.)

ration divisions. It is suggested that a comparable series of changes may exist in the egg mother cells and lead to the retention of all the chromosomes in the parthenogenetic egg-cells.

In the cultivated varieties of chrysanthemum, Tahara has found a polyploid series. In ten varieties (Fig. 97) nine haploid chromosomes are present, but the chromosomes themselves have different sizes, and, more important still, the relative size of the chromosomes may be different in different species (Fig. 98). This point will be considered later. It is also significant that the nuclear size may be different in some of these cases where the total number of chromosomes is the same. Other species of chrysanthemum have multiples of nine (Fig. 99); two species have 18, two have 27, one has 36, two have 45. The following table gives the relation between chromosome number and nuclear size.

Name	*Chromosome number*	*Nuclear diameter*	*Radius*^{3}
Ch. lavanduloefolium	9	5.1	17.6
Ch. roseum	9	5.4	19.7
Ch. japonicum	9	6.0	29.0
Ch. nipponicum	9	6.0	27.0
Ch. coronarium	9	7.0	43.1
Ch. carinatum	9	7.0	43.1
Ch. Leucanthemum	18	7.3	50.7
Ch. morifolium	21	7.8	57.3
Ch. Decaisneanum	36	8.8	85.4
Ch. arcticum	45	9.9	125.0

Triploid varieties of the mulberry (Morus) have been reported by Osawa. Of the 85 varieties studied, 40 are triploids. The diploid number of chromosomes is 28 (n=14) and the triploid 42 (3×14). The diploid plants are fertile, while the maturation divisions of the triploid show irregularities (univalent chromosomes) and have abortive pollen grains and embryo sacs. In the first matu-

ration division of the triploid, both in the pollen and in the megaspore mother cell, there are 28 bivalents and 14 univalents. The latter pass to the poles at random. They all divide at the second division.

In the maples (Acer) there appears to be a possible polyploid species. Taylor reported two species with 26 (n=13), two with 52 (n=26), and others with approximately 144 (n=72), or 108 (n=54), or 72 (n=36). Other species with different numbers were also found.

In the sugar cane (Saccharum) Tischler found races with the haploid numbers 8, 16, and 24 (bivalent) chromosomes. Bremer reports about 40 haploid chromosomes in another variety and 56 in a third. Other numbers have also been reported. Some of the combinations may be due to hybridization, but little is known at present to what extent the observed differences in number have arisen in this way. Bremer has also studied maturation divisions of a few hybrids.

In the genus Carex, Heilborn states that the chromosome numbers are quite different and that no apparent polyploid series exists in this genus. "It is of importance now to define somewhat more clearly the meaning of the word polyploid. It appears from the list of chromosome numbers in Chap. II that there are several numbers that constitute, apparently, a series of multiples with 3 as the fundamental number (9, 15, 24, 27, 33, 36, and 42), others, again, that form a series with 4 as fundamental number (16, 24, 28, 32, 36, 40, and 56), others with 7 (28, 35, 42, and 56) and so on, but, according to the author's opinion, these merely arithmetical relations cannot be regarded as cases of polyploidy. The chromosome group of a polyploid species must necessarily contain a certain number of complete haploid chromosome sets and it must have arisen through addition of such sets. We know, however, that, for instance, C. pilulifera does not contain 3 sets of

3 chromosomes, but 3 long, 4 medium, and 2 short chromosomes; that C. ericetorum does not contain 5 such sets, but 1 medium and 14 short chromosomes, and that, consequently, the chromosome groups in these two species have not arisen through an addition of such sets but in some other way.'' More problematical polyploid series are reported in Rumex, Papaver, Callitriche, Viola, Campanula, Lactuca. Two numbers, one of which is double or triple the other, have been found in Plantago (6, 12), Atriplex (9, 18), Drosera (10, 20), Platanthera (21, 63). It has also been recently reported by Longley that hawthorns and raspberries, known to be complex polymorphic species, show extensive polyploidy.

CHAPTER XII

HETEROPLOIDS

IRREGULARITIES in the division or the separation of the chromosomes occasionally cause a single chromosome to be added to the group. Conversely, one may be lost from the group. In so far as the addition of one or more chromosomes to, or loss from, a given group produces a new number, the word heteroploid has been used. Another word, trisomic, has also been used for cases where three of one kind are present (in contrast to triploid, where there are three of each kind present) and the word triplo combined with the name of the particular chromosome in triplicate has also been used, as triplo-IV in Drosophila. Still earlier, an extra chromosome was called a supernumerary or m-chromosome, etc. The loss of one member of a pair is designated by the term haplo- combined with the name of the particular chromosome, as in the haplo-IV type in Drosophila.

Certain mutant types of Oenothera have been found to be associated with the addition of a fifteenth chromosome.

Normally Lamarck's evening primrose has 14 chromosomes. Certain mutant types, known as lata and semilata, have 15 chromosomes, *i.e.*, one additional chromosome (Fig. 100). The lata plants differ from Lamarckiana in many small details, although most of the differences are so slight that only an expert would notice them. According to Gates, one of the lata mutants is almost completely male-sterile, and its production of seed is also greatly reduced. In one of the semi-lata types some good pollen is produced.

The frequency of occurrence of lata types varies in different progenies from 0.1 to 1.8 per cent, according to Gates.

At the maturation of the pollen of the 15 chromosome types, 8 chromosomes are present. Seven are in pairs

FIG. 100.
Oenothera lata. (After Anne Lutz.)

and 1 is unpaired. The conjugants separate and pass to opposite poles at the first maturation division. The unpaired chromosome does not divide at this time, but passes intact to one or to the other pole. Other irregularities in the maturation divisions occur in some cases, but whether or not they are caused by the extra chromosome is unknown, although Gates states that these irregu-

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larities are much more frequent in triplo-typic individuals than in normals.

From the 15 chromosome types two kinds of germ-cells are expected, one with 8, one with 7 chromosomes. It has been shown that these two kinds are produced. From a genetic standpoint the lata type, crossed to a normal type, should produce equal numbers of lata (8+7) and normal (7+7) offspring. This is approximately what happens.

The most interesting question concerning these triplotypes relates to the particular chromosome that becomes the supernumerary. Since there are seven kinds of chromosomes, we may anticipate that any one may appear in triplicate. De Vries has recently suggested that there are seven trisomic types in Oenothera, corresponding to the seven possible supernumeraries.

It is also important to bear in mind that types with two supernumeraries (either like or unlike), the tetrasomic types, may not be as viable as trisomic types. It is known that such types occur. For instance, amongst the offspring of a triplo-type there seems to be a good chance for the formation of an individual with two like supernumeraries when an 8-chromosome pollen grain fertilizes an 8-chromosome egg. This would give a tetra-type or tetrasomic group for one particular chromosome. It would be a stable type to the extent that 8 paired chromosomes are present in each germ-cell, but it might be even more unbalanced than a triplo-type with only one extra chromosome. Sixteen-chromosome types have been recorded, some of which are probably multiples of the same chromosome when they are derived from a 15 triplotype, but their relative viability is not recorded.

It seems, *a priori,* possible that duplication of any pair of chromosomes may be brought about through a triplotype giving rise to a tetratypic individual. But even if

stability should be attained, the more important factor of gene balancing may make it improbable that a permanent increase in the chromosome pairs could be established in this way. When a large chromosome number is present the initial stages of unbalancing might be slight as compared with forms having fewer chromosomes, because in the former the ratio would be less disturbed.

In Drosophila Bridges found a triplo-type for the small IV-chromosome, and since three genetic factors are present in this small chromosome it has also been possible to study not only the characters that are affected by the presence of an additional IV-chromosome, but the bearing of this condition on genetic questions in general. On the other hand, it has been found that an individual with three X-chromosomes usually dies, and that individuals with either chromosome-II or -III in triplicate do not live.

The triplo-IV Drosophila is not strikingly different from the normal, and the two can be distinguished only with difficulty. The general color of the body is a little darker and the trident marking on the thorax is absent (Fig. 32); the eyes are somewhat smaller and have a smooth surface; the wings are narrower and more pointed than those of the wild type. That these slight effects are due to the presence of an additional small chromosome was shown both by a cytological demonstration of its presence (Fig. 32) and by genetic tests. When a triplo-IV is crossed to eyeless (eyeless is a IV-chromosome recessive mutant type) some of the offspring (F_1) can be distinguished by the characters given above as triplo-IV flies. If these are back-crossed to eyeless (Fig. 33), flies with full eyes and flies with "eyeless eyes" are produced approximately in the ratio of 5 to 1. As shown in Fig. 33 this result agrees with expectation provided that one normal gene is dominant to two eyeless genes.

When two triplo-IV flies (obtained in the way described above) that have two ordinary IV-chromosomes and another IV-chromosome carrying eyeless, are mated, they give approximately 26 full-eyed flies to one eyeless.

From this cross some flies might be expected that contained four chromosome-IV's, since half of the eggs and half of the sperm-cells carry two of these chromosomes. If such tetra-typic flies developed, the expected ratio would be 35 full-eyed to one eyeless. The ratio found (26 to 1) instead of the expected ratio (on the assumption that the tetra-typic flies come through) is due to the death of the tetra-types. In fact, no flies of this composition have been detected, which means that, despite the smallness of these chromosomes, the presence of four of them upsets the balance of the genes to such an extent that such an individual does not develop into an adult.

In contrast to these triplo-types of Drosophila there is another heteroploid type, the haplo-IV type (Fig. 29), in which one of the small chromosomes is absent. This type has appeared very often, which is interpreted to mean that one of these small chromosomes is sometimes lost in the germ track—possibly as a result of two passing to one pole at the reduction division. The haplo-IV has a paler body color but a more marked trident on the thorax, rather large eyes with a rough surface, slender bristles, and somewhat shortened wings, and the aristae are reduced or even absent. In all these respects its characters are the opposite of those of the triplo-type. This is not at all surprising if the IV-chromosome contains genes that affect many parts of the body in conjunction with other genes. These effects are increased by the presence of an additional chromosome and diminished when one is absent. The haplo-IV's emerge four or five days later than the normals; they are often sterile and generally poor producers; their mortality is very high. There is abun-

dant cytological and genetic evidence that these flies owe their peculiarities to the absence of one chromosome.

Flies lacking both IV-chromosomes have not been found and the ratio obtained when two haplo-IV's are bred together (giving 130 haplo-IV's to 100 normals) shows that the nullo-IV's die.

If a diploid fly that is eyeless is mated to a haplo-IV fly carrying wild type genes in its single chromosome-IV, some of the F_1 offspring will be eyeless and these will be haplo-IV. Theoretically, half of the offspring should be eyeless, but the presence of the eyeless gene in the single fourth chromosome lowers the viability of the haploid 98 per cent of expectation, and this relation holds when the other recessive mutant types (bent and shaven) are present in the single IV-chromosome. According to Bridges, bent lowers survival by 95 per cent and shaven, 100 per cent, *i.e.,* haplo-shaven does not develop.

The Jimson weed, Datura stramonium, has 24 chromosomes. A number of types under cultivation have been detected by Blakeslee and Belling with 25 chromosomes (2n+1). It is probable that there are 12 such types, each of which has a different extra chromosome. The slight but constant differences shown by these 12 triplo-types (2n+1) involve all parts of the plant. These differences are well shown in the capsules (Fig. 101). In two of these, at least (triplo-globe and triplo-poinsettia), in which Mendelian factors are present in the extra-chromosome group, it has been shown by Blakeslee, Avery, Farnham, and Belling, that the twenty-fifth chromosome involved is a different one in the two cases. In one of these in particular, namely, the trisomic type poinsettia, involving a chromosome that carries the gene for purple stem pigment and white flower color, the effects on the inheritance due to one extra chromosome have given the clearest results. These show that those germ-cells carrying the extra chro-

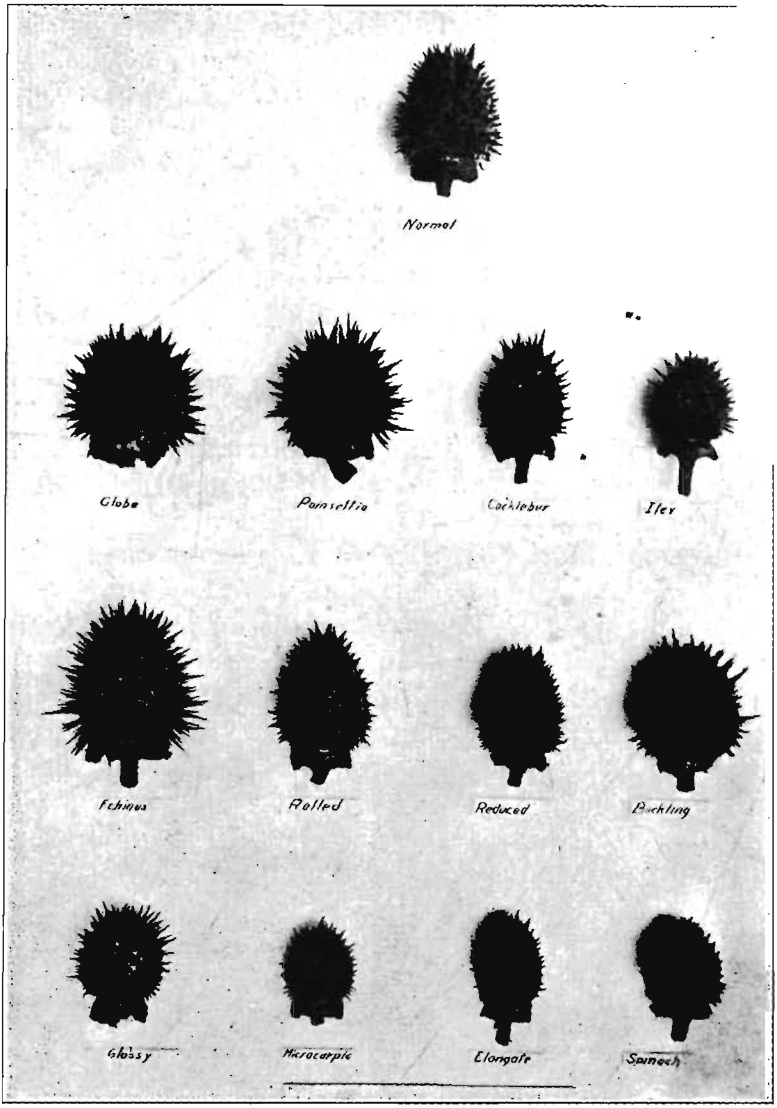


FIG. 101.

The original type of seed-capsule of Datura stramonium, and the twelve probable trisomic types. (After Blakeslee, in Journal of Heredity.)

mosome are less viable than the normal, hence deficiencies in certain expected classes occur; in fact, these germ-cells (n+1) are not transmitted at all through the pollen

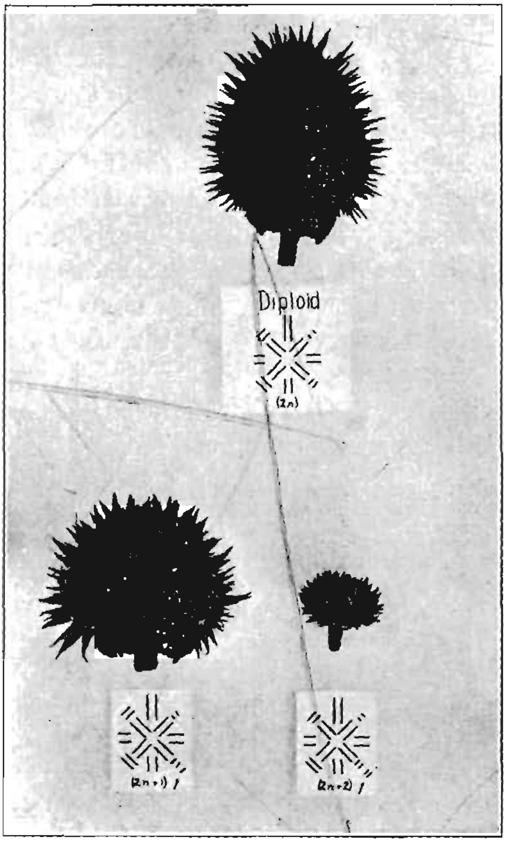


Fig. 102.

Diploid type of capsule of Datura (2n) as contrasted with 2n+1 and 2n+2 types of capsule. (After Blakeslee, in Journal of Heredity.)

(or only to a slight extent), and through only about 30 per cent of the eggs. When these relations are allowed for, the genetic results agree with expectation.

In their study of the trisomic types of Datura, Blakeslee and Belling have found about 12 distinct types belonging to the 2n+1 or trisomic series. Since there are just 12 pairs of chromosomes, only 12 simple trisomic types are expected, and, in fact, evidence has been found that there are only 12 such primary types. The rest, called secondaries, appear to belong to one or another of the 12 primary types (Fig. 102). The evidence for this comes from several sources, from similarities in external appearance, from internal structures (as shown by Sinnott), from their similar mode of inheritance (giving the same trisomic inheritance for marked chromosomes), from the reciprocal throwing of one member of the group by the other, and from the sizes of the extra chromosomes (Belling).

In the following table a list of the primaries and their secondaries is given. These have been derived from triploids.

Primary and Secondary (2n+1) Types in Offspring from Triploids
(Primaries are printed in capitals, secondaries in lower case type.)

	3n × self	3n × 2n	Total
1. GLOBE	5	46	51
2. POIN-SETTIA	5	34	39
Wiry	..	..	..
3. COCKLE-		32	38
BUR	6	1	1
Wedge	..	33	37
4. ILEX	4		
5. ECHINUS	3	15	18
Mutilated	..	(2?)	(?)
Nubbin (?)	..	..	..
6. ROLLED	..	24	24
Sugarloaf	..	..	..
Polycarpic	..	..	..
7. REDUCED	3	38	41

	3n × self	3n × 2n	Total
8. BUCKLING	9	48	57
Strawberry	..	...	...
Maple	..	...	...
9. GLOSSY	2	30	32
10. MICRO-CARPIC	4	46	50
11. ELONGATE	2	30	32
Undulate	..	...	...
12. SPINACH(?)	..	2	2
Totals (2n + 1)	43	381	424
(2n + 1 + 1)	11	101	112
2n	30	215	248
4n	3	...	3
Grand Totals	87	697	784

The spontaneous occurrence of primaries and secondaries is given in the next table. The primaries arise in this way more frequently than the secondaries. Breeding experiments have shown that whereas primaries may occasionally throw secondaries, the secondaries regularly throw their primaries more frequently than they throw new mutants belonging to the other groups. Thus of 31,000 offspring from poinsettias about 28 per cent were poinsettia and about 0.25 per cent were the secondary wiry. Conversely, when wirys were the parents about 0.75 per cent of the offspring were the primary poinsettia.

Spontaneous Occurrence of Primary and Secondary (2n+1) Mutants
(Primaries are printed in capitals, secondaries in lower-case type.)

	From 2n parents	From unrelated (2n + 1) parents	Totals
1. GLOBE	41	107	148
2. POINSETTIA	28	47	75
Wiry	..	1	1
3. COCKLEBUR	7	17	24
Wedge	..	..	..
4. ILEX	19	27	46
5. ECHINUS	10	11	21
Mutilated	2	4	6
Nubbin(?)	1	..	1
6. ROLLED	24	47	71
Sugarloaf	3	9	12
Polycarpic	3	..	3
7. REDUCED	25	44	69

	From 2n parents	From unrelated (2n + 1) parents	Totals
8. BUCKLING	27	71	98
Strawberry	1	1	2
Maple	..	2	2
9. GLOSSY	8	11	19
10. MICROCARPIC	64	100	164
11. ELONGATE	..	2	2
Undulate	..	1	1
12. SPINACH(?)	6	4	10
Totals (2n + 1)	269	506	775
Related (2n + 1) types	....	22,123	22,123
2n	32,523	70,281	102,804
Grand totals	32,792	92,910	125,027

The breeding experiments of Wedge—a Secondary of the Cocklebur group—furnishes the following evidence as to the relation of secondaries to primaries. "Both Poinsettia and its Secondary Wiry give trisomic ratios for the color factors P, p, but give disomic ratios for

spine factors A, a, indicating that both Poinsettia and Wiry have their extra chromosomes in the set carrying the factors P, p, but not in the set with the factors A, a. Similarly, the ratios for Cocklebur indicate that this Primary has its extra chromosome in the set carrying the factors A, a, but not in the set with factors P, p. Its Secondary Wedge, however, fails to give trisomic ratios for A, a. The ratios actually found resemble those in disomic rather than in trisomic inheritance and seem to indicate a deficiency in the extra chromosome of Wedge for the locus A, a, since the evidence strongly indicates that it is a Secondary of Cocklebur. If A′ indicates the modified chromosome and A and a go to opposite poles at reduction division in a Wedge plant with the formula AA′a, the gametes would be A+a+AA′+aA′. Such behavior would account for the ratios [in table 5]. If A′ is deficient for the factor A, the gamete aA′ would carry no factor for A; hence the disomic ratios between armed and *inermis* Wedges found but not shown in the table. If A and a, occasionally should go to the same pole, the gametes would be A′ (which would probably die) and Aa, which would go to form a Primary Cocklebur occasionally thrown by Wedges.

"The hypothesis of a deficiency in the extra chromosome of Secondaries has been strengthened by Dr. Belling's cytological findings. His hypothesis of reversed crossing-over, however, completes the picture by indicating a doubling of a part of the chromosome along with a deficiency of the remaining portion."

Tetraploids of Datura with an additional chromosome have also been reported (Fig. 103). In one of these shown in the figure there are five like chromosomes in one group, and in the other there are six like chromosomes.

Belling and Blakeslee have studied the modes of union of the three chromosomes in the primary and in the sec-

ondary trisomic types of Datura, and have found certain differences that offer a suggestion as to the relation of these two types. In the upper row of Fig. 104 the differ-

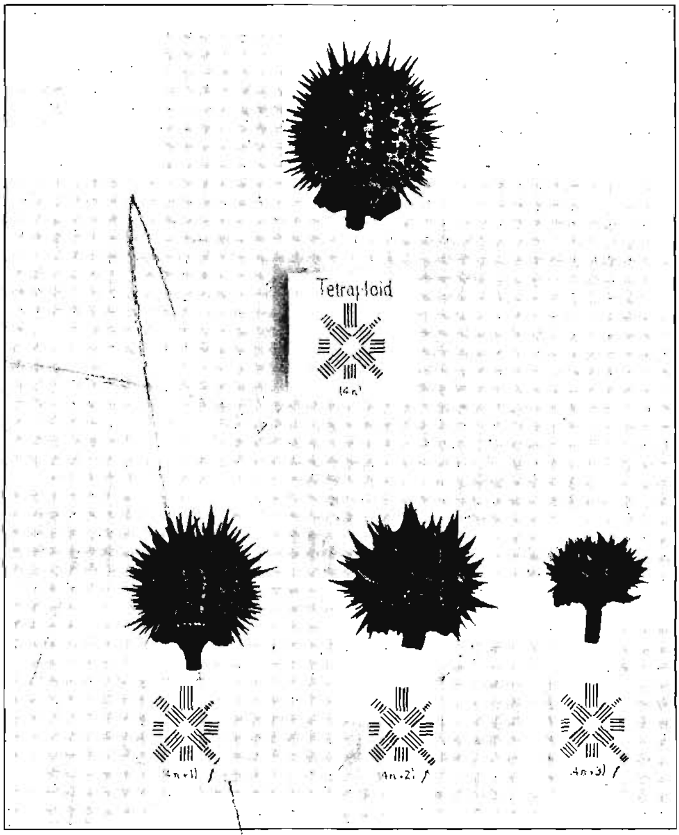


Fig. 103.

Tetraploid capsule above, and below 4n+1, 4n+2, and 4n+3 capsules. (After Blakeslee, in Journal of Heredity.)

ent ways in which the three chromosomes of the primary type are united are shown. The numbers below each show the frequency of the type. Of these types the triva-

lent V is the most common form of union (48); next in frequency is the ring-and-rod type (33); then the Y (17); the straight chain (9); the ring (1); the double ring (1); the ring of two with the third member left over (9+).

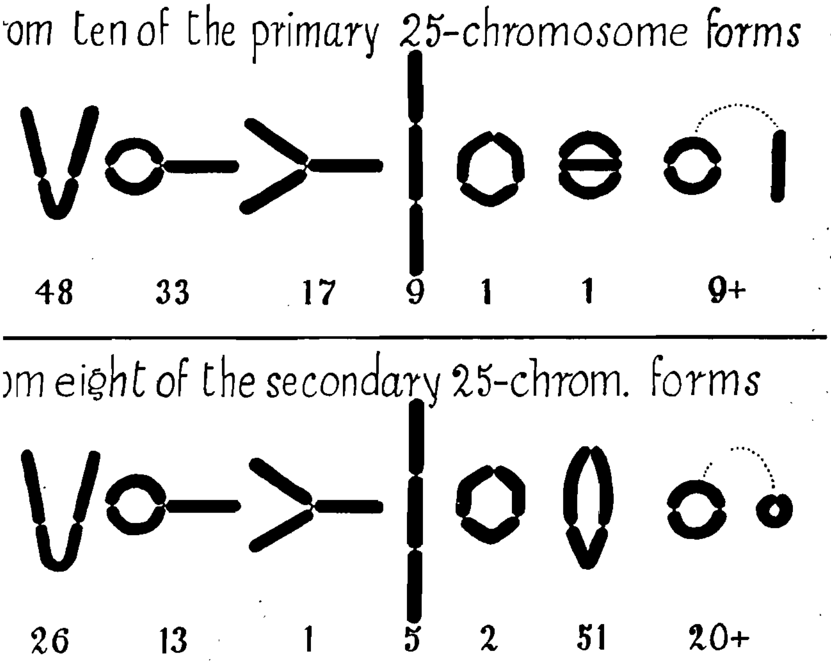


FIG. 104.

Methods of union of the three chromosomes of a trisomic type of Datura. (After Belling and Blakeslee.)

Since chromosomes are supposed to conjugate by like ends coming together it is reasonable to assume that, in these types, like ends (a and a, Z and Z) are still in contact (see Fig. 104, upper row).

In the lower row of Fig. 104 the different ways in which the three chromosomes of the secondary types are united are shown. In general the types are the same as those of

the primaries, but the frequencies are different. The most noticeable features are seen in the last two types (to the right). One of these is an elongated ring of three chromosomes, the other is a ring of two chromosomes and a small single-ring chromosome. These two types suggest

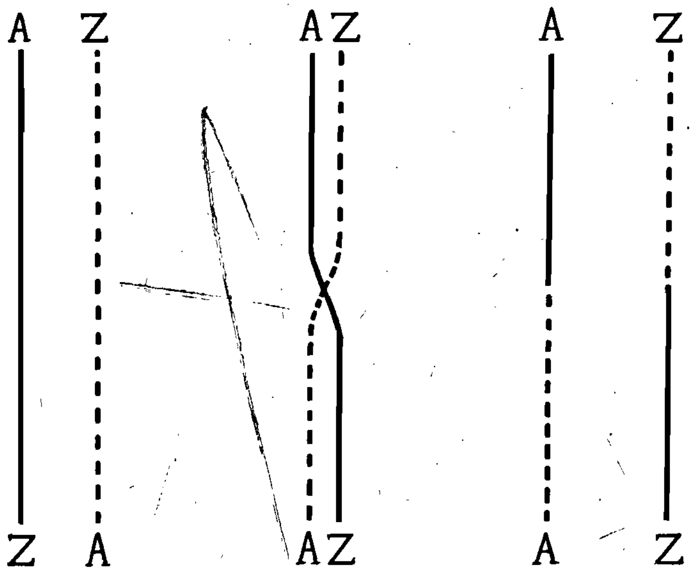


FIG. 105.

Diagram illustrating possible conjugation of two chromosomes, turned in opposite directions.

that, in some way, the end of one chromosome has been changed. Belling and Blakeslee offer the following provisional suggestions as to how such a change may have been brought about at a preceding stage in the triploid parent or in a trivalent of a primary type. Suppose, for example, two chromosomes should come to lie side by side in reversed position as shown in Fig. 105, and suppose they should cross over in the middle, which is the only level

at which like genes come together. The result will give two chromosomes each having its two ends alike, *i.e.*, one has A and A at its ends, the other Z and Z. If now such a chromosome becomes in the next generation a member

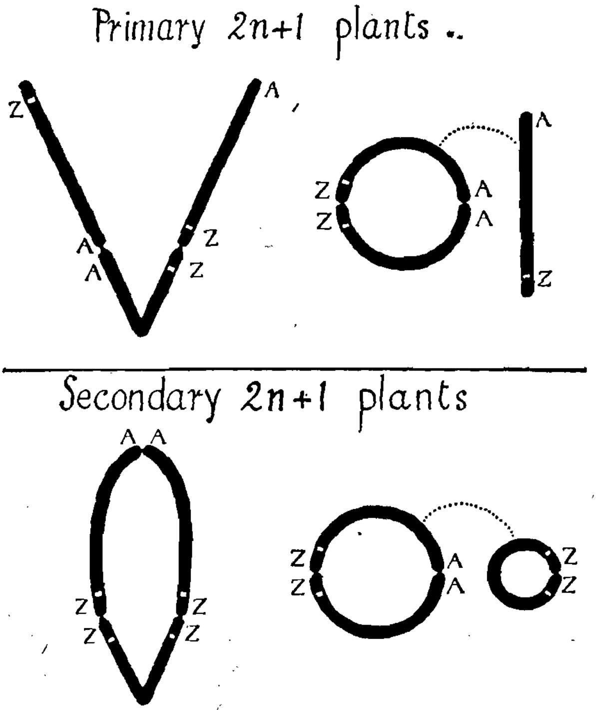


FIG. 106.

Diagram illustrating possible types of conjugation of three chromosomes of trisomic types. (After Belling and Blakeslee.)

of a trivalent group, it is possible to construct such modes of union as indicated in Fig. 106, where in a Z-Z chromosome, combined with two normal partners, like ends meet each other.

If these rings, peculiar to the secondaries, can be accounted for in the way suggested, it follows that one of

the trivalent chromosomes differs from the other two by a duplicated half. Hence the secondary has a different gene combination from the primary.

Kuwada reports 20 chromosomes (n=10) for corn (Zea mays), but certain sugar corns were found to have 21, 22, and even 23 or 24 chromosomes. Kuwada suggests that corn is a hybrid, one of whose parents was the Mexican teosinte (Euchlaena). One of the corn chromosomes that is longer than its mate was derived from teosinte, he thinks, and its mate from some unknown species. The longer one sometimes breaks into two pieces, which accounts for the additional chromosomes found in sugar corns. If this interpretation is verified (it has recently been questioned), these 21, 22, and 23 chromosome types are not strictly trisomic.

De Vries' conclusions relating to the extra chromosome types of Oenothera Lamarckiana had an important bearing on his interpretation of the origin of progressive mutation, hence on his interpretation of the relation of mutation to evolution. The numerous small changes in the characters of the individual frequently observed in trisomic types fulfill de Vries' early definition as to what constitutes an elementary species, causing at a stroke, as it were, the appearance of two elementary species.

It should be observed that when a mutational effect is produced by the addition of a whole chromosome the result involves, so far as the germ material is concerned, an enormous alteration in the actual number of the hereditary units. This change is scarcely compatible with the comparison to a change in a single chemical molecule. Only by treating the chromosomes as a unit could such a comparison have any weight. The constitution of the chromosomes, from the viewpoint of their genes, is hardly consistent with such a comparison.

The chief interest in these heteroploids, as I interpret

them, lies in the explanation they offer of a peculiar and interesting genetic situation arising from the occasional erratic behavior of the mechanism that is involved in the processes of cell division and maturation. Unstable forms are produced, that, in so far as they maintain themselves, do so by remaining unstable, *i.e.,* with an extra chromosome. In this respect they differ obviously from normal

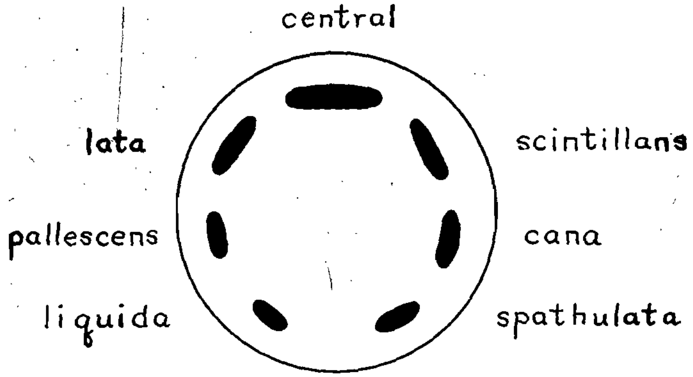


FIG. 107.

Diagram illustrating de Vries' idea of the relation between the seven chromosomes of O. Lamarckiana and types of trisomic mutants. (After de Vries and Boedijn.)

types and species. Furthermore, most of the evidence indicates that these heteroploids are not so viable as the balanced types from which they arise, hence would rarely be able to replace them or act as substitutes in a different environment.

Nevertheless, the occurrence of heteroploidy must be regarded as a significant genetic event whose explanation promises to clear up many situations that would be very puzzling without the information which a study of their chromosomes has revealed.

De Vries identifies six trisomic mutant types, and a seventh one, also, that differs genetically more strikingly from the other six than they do from each other. These seven trisomic types may, he suggests, correspond to the seven chromosomes of the evening primrose. A list of six of them is given below. A diagram of the corresponding chromosome groups is given in Fig. 107.

15-chromosome mutants.

1. Lata group.
   - a. Semi-lata.
   - b. Sesquiplex mutants: **albida, flava, delata.**
   - c. Subovata, sublinearis.
2. Scintillans group:
   - a. Sesquiplex mutants: oblon**ga, aurita, auric**ula, nitens, distans.
   - b. Diluta, militaris, venusta.
3. Cana group: candicans.
4. Pallescens group: lactuca.
5. Liquida.
6. Spathulata.

This list of six 15-chromosome primary mutants includes some secondary mutant types arranged under their primaries. Their interrelations are shown not only by similarities in characters, but also by the frequency with which one throws the other. Two of them, albida and oblonga, have two kinds of eggs but only one kind of pollen, and are called one-and-one-half or sesquiplex mutants. Another secondary, candicans, is also a sesquiplex type. The central or largest "chromosome" of the group (Fig 107) carries the "factors" for velutina or for those of laeta. De Vries assigns to them also, from evidence found by Shull, the new mutants funifolia and pervirens. It may seem probable, therefore, following Shull, that

the factors for five other mutant types[1] of Lamarckiana belong in this group, as well as the lethal factors that put these factors in a balanced lethal condition. According to Shull the appearance of these recessive characters is due to crossing-over between the members of a pair of chromosomes here identified provisionally as the large central chromosome.

[1] Rubricalyx buds, and its allelomorph red stem (intensifier), nanella (dwarf), pink-coned buds, sulfur colored flowers.

CHAPTER XIII

SPECIES CROSSING AND CHANGES IN CHROMOSOME NUMBER

SOME interesting relations have come to light as a result of crossing species having different chromosome numbers. One species may have exactly twice or three times as many chromosomes as the other; in other cases, the larger chromosome group may not be a multiple of the other.

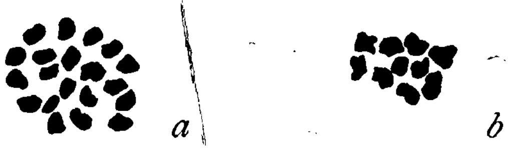


FIG. 108.

Diploid and haploid groups of the sundew, Drosera rotundifolia. (After Rosenberg.)

The classic case is that of the cross between two species of sundew by Rosenberg in 1903-1904.

One species of sundew, Drosera longifolia, has 40 chromosomes (n=20), another species, rotundifolia, has 20 chromosomes (n=10) (Fig. 108). The hybrid has 30 chromosomes (20+10). In the maturation of the germ-cells of the hybrid, there are 10 conjugating chromosomes, often called gemini or bivalents, and 10 singles (univalents). Rosenberg interpreted this condition to mean that 10 of the longifolia unite with 10 of the rotundifolia leaving 10 of the former without a mate. At the first maturation division of the germ-cell, the conjugants

separate, the members going to opposite poles; the 10 single chromosomes are distributed irregularly, without division, to the daughter cells. Unfortunately the hybrid is sterile, and cannot be used for further genetic work.

The cross between two species of tobacco, Nicotiana Tabacum and N. sylvestris, has been extensively studied by Goodspeed and Clausen. Only recently, however, has the chromosome number been determined; Tabacum has 24 (n=12) and sylvestris 48 (n=24) chromosomes. This difference in chromosome number has not as yet been correlated with the genetic results; and the behavior of the chromosomes in the maturation divisions has not been reported.

The hybrid from crossing these two species resembles in every particular the Tabacum parent, even when that parent is pure for factors that behave as recessives toward the normal factors of the type Tabacum (*i.e.*, in crosses with varieties or races of Tabacum). Goodspeed and Clausen interpret this result to mean that the Tabacum genes dominate as a group the sylvestris genes. They have expressed this by saying that the "reaction system" of Tabacum dominates the embryological processes of the hybrid; or "the elements of the two systems must be largely mutually incompatable."

The hybrids are highly sterile, but a few functional ovules are formed. As the breeding results show, these functional ovules are exclusively (or predominately) either pure Tabacum or pure sylvestris. It may seem, therefore, that in the hybrid only those (or largely only those) ovules that contain a complete set (or nearly complete set) of one or the other group of chromosomes are functional. This view is based on the following experiments.

When the hybrid is fertilized with the pollen of sylvestris, a variety of forms is produced, among which there

is a considerable proportion of plants that are pure sylvestris in all their characters. These plants are fertile and breed true to sylvestris. They must be supposed to have come from ovules with a sylvestris chromosome group, fertilized by sylvestris pollen. There are also plants that resemble sylvestris, but contain other elements, probably derived from the Tabacum group of chromosomes. They are sterile.

Back-crossing to Tabacum was unsuccessful, but a few hybrids have appeared in the field from open pollination that are like Tabacum and have undoubtedly come from Tabacum pollen. Some of them are fertile. Their descendants never show sylvestris characters. They exhibit segregation for whatever Tabacum genes were present. There are also sterile forms in the series, and these resemble the F_1 hybrids between Tabacum and sylvestris.

These remarkable results are important in another respect. The F_1 hybrid may be obtained both ways; *i.e.*, either species may be the ovule parent. It follows that even with a sylvestris protoplasm the Tabacum group of genes completely determines the character of the individual. This is strong evidence in favor of the influence of the genes in the determination of the character of the individual, since this result is obtained when the protoplasm belongs to a widely different species.

The idea of a reaction system, proposed by Clausen and Goodspeed, while novel, contains nothing in principle that is opposed to the general interpretation of the gene. It means only that the haploid set of genes of sylvestris, when placed in opposition to the haploid set of genes of Tabacum, is totally eclipsed and ineffectual. The sylvestris chromosomes, nevertheless, retain their identity. They are not eliminated or injured, since from the hybrid a set of functional sylvestris chromosomes may be regained in back-crosses to a sylvestris parent.

An extensive series of crosses between species of Crepis have been carried out by Babcock and Collins. The chromosomes of these hybrids have also been studied by Miss Mann (1925).

Crosses between Crepis setosa with 8 chromosomes ($n=4$), and C. capillaris with 6 chromosomes ($n=3$) have been made by Collins and Mann. The hybrid has 7 chromosomes. At maturation some of the chromosomes conjugate and other chromosomes, without dividing, are scattered in the pollen mother cells, forming nuclei with from two to six chromosomes. At the second division all the chromosomes divide, at least, those in the larger groups, and pass to opposite poles. The cytoplasm usually divides into four cells, but sometimes into 2, 3, 5, or 6 microspores.

These 7-chromosome hybrids do not give functional pollen, but some of the ovules are functional. When the hybrid was used as pistil parent and fertilized by pollen from one of the parents, five plants were obtained with 8 and 7 chromosomes. The maturation stage of one with 8 chromosomes was examined. It had 4 bivalents, which divided normally. The plant resembles C. setosa in its characters and has the same type of chromosomes. One of the parental types has been recovered.

Another cross was made between Crepis biennis with 40 chromosomes ($n=20$) and C. setosa with 8 chromosomes ($n=4$) (Fig. 109). The hybrid has 24 chromosomes ($20+4$). In the maturation of the hybrid, at least 10 bivalents are present, and a few univalents. It follows that some of the biennis chromosomes must conjugate with each other, since setosa contributes only 4 chromosomes. At the ensuing division 2 to 4 chromosomes lag behind the rest, but finally pass, in most cases, to one or the other nucleus.

The hybrids are fertile. They produce (F_2) plants hav-

ing 24 or 25 chromosomes. There seems to be a chance here of producing new stable types with a new chromosome number that may contain one or more pairs of chromosomes derived from the species contributing the

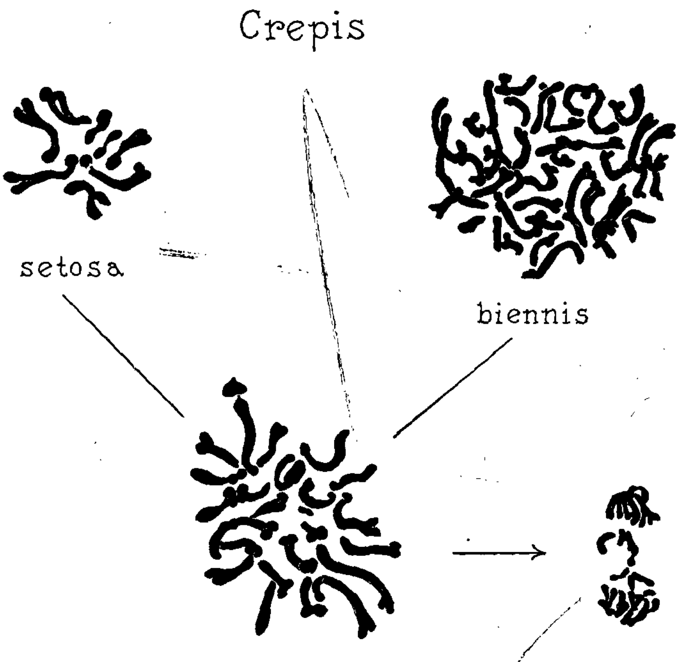
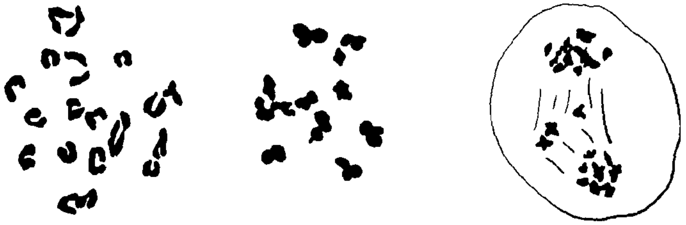


FIG. 109.
Chromosome groups of Crepis setosa and C. biennis. (After Collins and Mann.)

smaller number. The presence of 10 conjugants in the hybrid suggests that Crepis biennis is a polyploid, possibly an octoploid. In the hybrid the like chromosomes unite in pairs. This F_1 hybrid, with half the full number of biennis chromosomes, is an annual, while biennis itself is biennial. The reduction in the number of its chromosomes has caused a change in its habits. It reaches maturity in half the time necessary for biennis.

Two types of Mexican teosinte have been described by Longley, one, mexicana, an annual type with 20 chromosomes (n=10), the other, perennis, a perennial with 40 chromosomes (n=20). Both plants have normal reduction divisions. When the diploid teosinte (n=10) is crossed to Indian corn (n=10), the hybrid has 20 chromosomes. At maturation, there are 10 bivalents in the hybrid's germ-cells. This would ordinarily be interpreted to mean that 10 chromosomes of teosinte have united with 10 of Indian corn.



a *b* *c*

FIG. 110.

Reduced chromosome group, *a*, of perennial teosinte; *b*, of hybrid with maize; *c*, reduction division of last. (After Longley.)

When the perennial teosinte (n=20) is crossed to Indian corn (n=10) the hybrid has 30 chromosomes. At the first maturation division of the pollen mother cells there were found some trivalent groups loosely held together, some bivalents, and some single chromosomes in varying numbers, thus as 4 : 6 : 6; or as 1 : 9 : 9; or as 2 : 10 : 4, etc.; see Fig. 110b. At the first division the bivalents divide and the partners move to opposite poles; the trivalents divide, two going to one pole, one to the other; the singles lag and are distributed (without division) irregularly to the two poles (Fig. 110c). A very unequal distribution results.

Quite recently a case has been described in which a

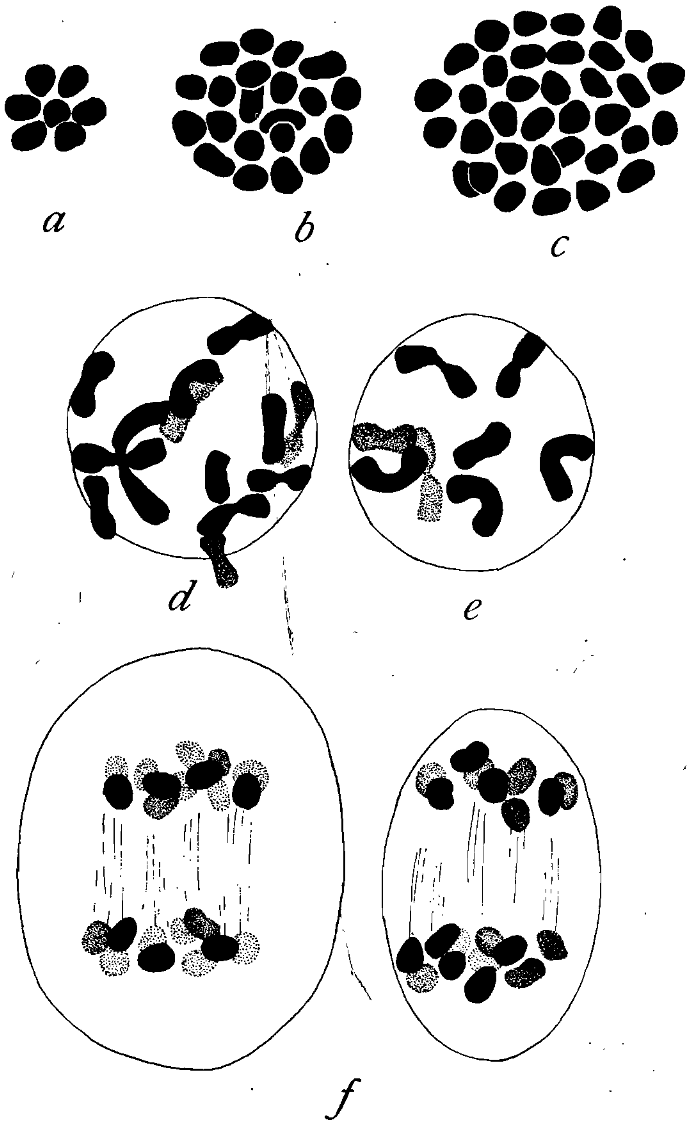


FIG. 111.

Cross between two species of poppies, one, *a*, Papaver nudicaule, having 14 chromosomes (n=7) and the other, *c*, P. striatocarpum having 70 chromosomes (n=35). The hybrid, *b*, has 42 (n=21). *d-e*, embryo mother cell of hybrid. *f*, first maturation division of hybrid, anaphase. (After Ljungdahl.)

new stable hybrid that is fertile has been produced by crossing two species with widely different chromosome numbers. Ljungdahl (1924) crossed Papaver nudicaule, having 14 chromosomes (n=7), with P. striatocarpum, with 70 chromosomes (n=35) (Fig. 111). The hybrid has 42 chromosomes. At maturation of the hybrid germ-cells there are 21 bivalents (Fig. 111, b, c-e). These divide, 21 going to each pole. No single chromosomes are present, and none lag on the spindle. The result must be interpreted to mean that the 7 chromosomes of nudicaule have mated with 7 chromosomes of striatocarpum, and that the remaining 28 chromosomes of striatocarpum have conjugated in twos to give 14 bivalents. This gives a total of 21 bivalents, the number observed. It seems natural to assume that the form striatocarpum, with 70 chromosomes (n=35), is probably a decaploid type, *i.e.*, a type with ten times each kind of chromosome.

The new type (F_1) produces germ-cells with 21 chromosomes. It is balanced and stable. It is also fertile and may be expected to produce a new stable type. From it still other stable types are theoretically possible. If back-crossed to nudicaule it should give rise to a tetraploid type (21+7=28). Back-crossed with striatocarpum it should produce an octoploid type (21+35=46). Here, through hybridization of a diploid and a decaploid type, there may be produced in subsequent generations tetraploids, hexaploids, and octoploid types that are stable.

Federley's experiment (Chapter IX) with species of moths of the genus Pygaera illustrate a very different relation. Owing to the failure of the chromosomes to conjugate in the germ-cells of the hybrid the double number is retained. By back-crossing the double number may be continued, but as the hybrids are very sterile nothing permanent could result from these combinations under natural conditions.

CHAPTER XIV

SEX AND GENES

OUR present understanding of the mechanism of sex-determination has come from two sources. Students of the cell have discovered the rôle played by certain chromosomes and students of genetics have gone further and have discovered important facts as to the rôle of the genes.

Two principal types of mechanism for sex-determination are known. They both involve the same principle, although they may seem, at first, to be the converse of each other.

The first type may be called the insect type, because in insects we have the best cytological and genetic evidence for this kind of sex-determining mechanism. The second type may be called the avian type, because in birds we now have both cytological and genetic evidence for this alternative mechanism. It is also present in moths.

The Insect Type (XX-XY).

In the insect type the female has two sex-chromosomes that are called X-chromosomes (Fig. 109). When the eggs of the female ripen (that is, after each has given off its two polar bodies), the number of the chromosomes is reduced to one-half. Each ripe egg, then, contains one X and, in addition, one set of ordinary chromosomes. The male has one X-chromosome only (Fig. 112). In some species this X has no mate; but in other species it has a mate that is called the Y-chronlosome (Fig. 113). At one of the maturation divisions the X and the Y pass to oppo-

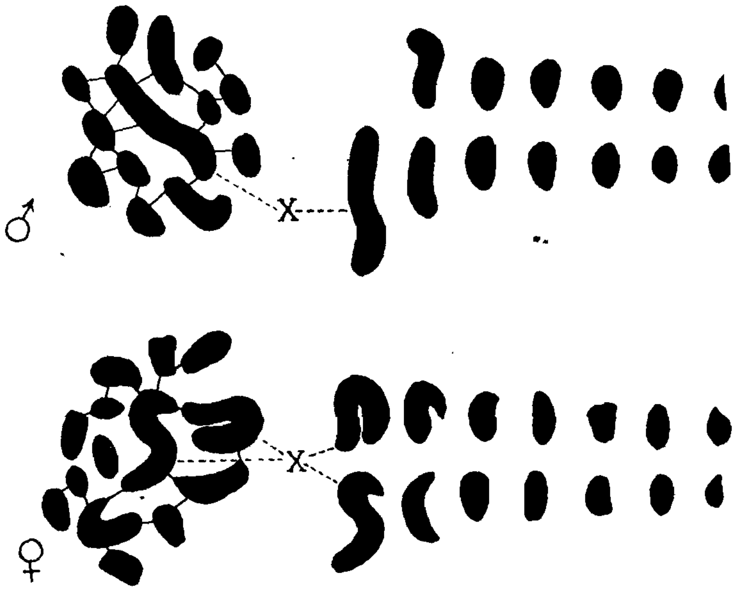


FIG. 112.

Chromosome group of male and of female Protenor, the former having one X-chromosome and no Y-chromosome; the latter having two X-chromosomes. (After Wilson.)

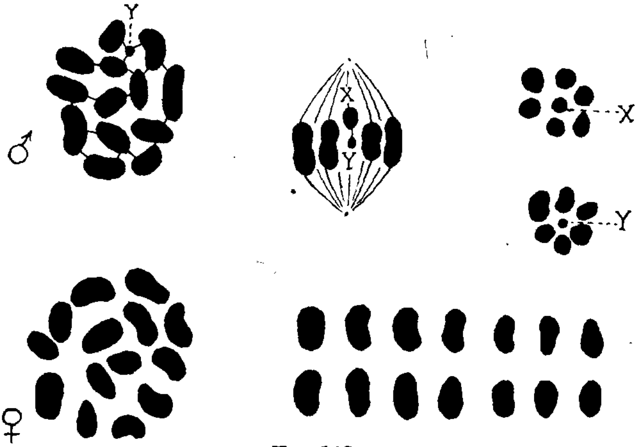


FIG. 113.

The male and female type of chromosome groups of Lygaeus, the former with X and Y; the latter with two X-chromosomes. (After Wilson.)

site poles (Fig. 113). One daughter cell gets the X, the other the Y. At the other maturation division each splits into daughter chromosomes. The outcome is four cells that later become spermatozoa; two contain an X-chromosome, two contain a Y-chromosome.

Any egg fertilized by an X-sperm (Fig. 114) gives rise to a female that has two X's. Any egg that is fertilized

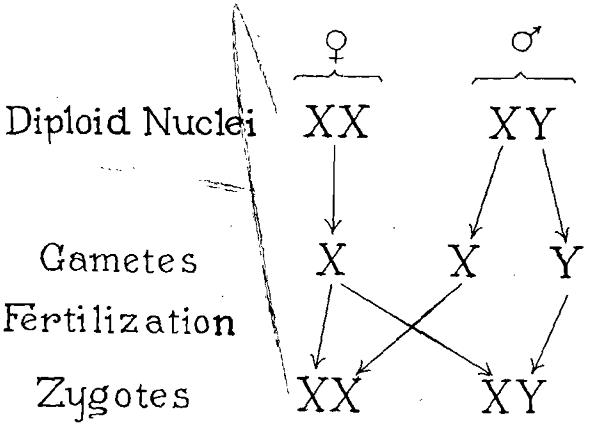


Fig. 114.
Diagram illustrating the XX-XY type of mechanism in sex determination.

by a Y-sperm gives rise to a male. Since the chances are equal that an egg will be fertilized by one or the other kind of sperm, the expectation is that half the offspring will be female and half will be male.

Given such a mechanism, certain kinds of inheritance are explicable, some of them including ratios that do not appear, at first sight, to conform to Mendel's 3 to 1 ratio. On closer scrutiny, however, the apparently exceptional ratios are found to furnish confirmation of Mendel's first law. For instance, if a white-eyed female of Drosophila is bred to a red-eyed male, the female offspring are red-eyed and the sons are white-eyed (Fig. 115). The

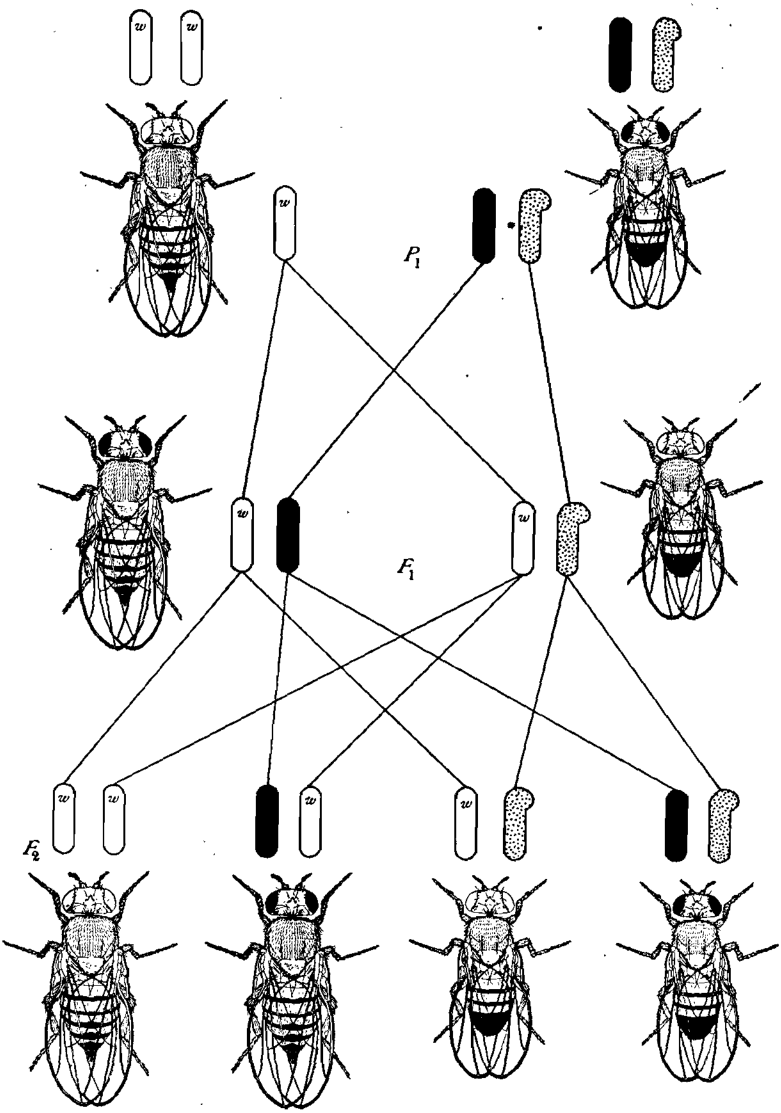


FIG. 115.

Inheritance of the white-eyed character in Drosophila. The gene for white eye is carried by the X-chromosome represented here by an open rod (w). The normal allelomorph to the "white-eyed gene," namely, the "red-eyed gene" is carried here by the black rod. The Y-chromosome is stippled.

explanation is obvious, if the X-chromosomes carry the differential genes involved, namely, the red- and white-producing genes. The son gets his single X from his white-eyed mother; and the daughter gets also such an X, but also one from her red-eyed father. The latter being dominant, the daughter has red eyes.

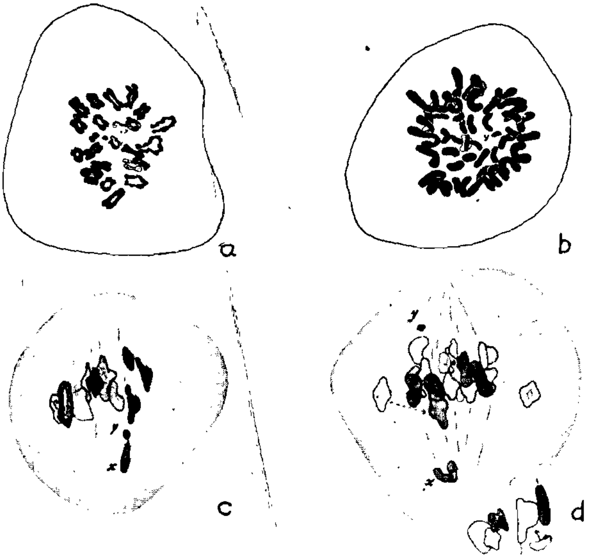


FIG. 116.

a, The reduced group of chromosomes in man, according to de Winiwarter; b, chromosome group in man, according to Painter; c and d, side view of first maturation division showing the separation of the X- and Y-chromosomes, according to Painter.

If these two individuals are inbred there will appear in the next generation white-eyed and red-eyed offspring in the ratio of 1:1:1:1. This ratio is due to the distribution of the X-chromosomes, as shown in the middle of the diagram (Fig. 115).

In passing, it is not without interest to note that the cytological evidence and the genetic evidence, especially

the latter, show that man belongs to the XX-XO or to the XX-XY type. The number of chromosomes in the human race has only recently been determined with any degree of accuracy. The earlier observations giving fewer have

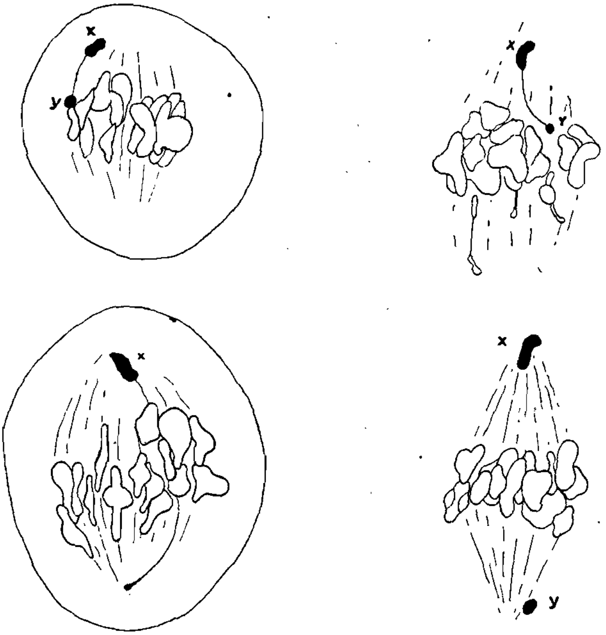


FIG. 117.

Maturation division of the germ-cells of man, illustrating the separation of the X- and the Y-chromosome. (After Painter.)

been shown to be faulty, owing to the tendency of the chromosomes to stick together in groups when the cells are preserved. De Winiwarter gives the number as 48 in the female (n=24) and 47 in the male (Fig. 116a), and this count is practically confirmed by Painter, who recently has shown that there is also present in the male a small chromosome that acts as the mate of a much

larger X (Fig. 117). He interprets these two as an XY pair. If so, there are 48 chromosomes in each sex, but in the male those of one pair, the sex-chromosomes, are unequal in size.

More recently still Oguma, who confirms de Winiwarter's numbers, finds no Y-chromosome in the male.

The genetic evidence for man is quite clear. The inheritance of haemophilia (or bleeding), of color blind-

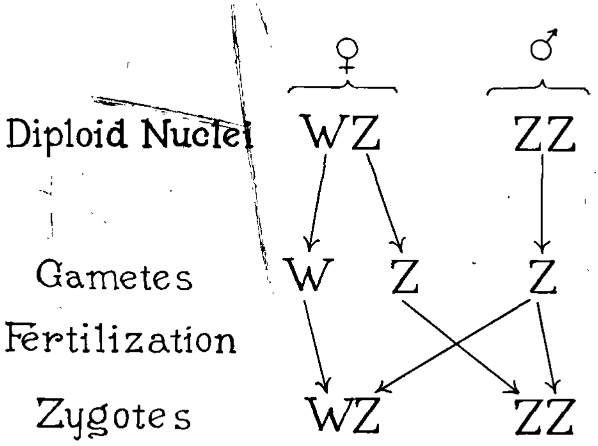


FIG. 118.
Diagram illustrating the WZ-ZZ type of mechanism in sex determination.

ness, and of two or three other human characters, follow in their inheritance the same method of transmission seen in the white-eyed flies.

The following groups of animals belong to the XX-XY type or to a modification of this type, *viz.*, the XX-XO type, in which O means the absence of Y or no X. Several mammals in addition to man have been reported to have this mechanism—the horse and the opossum, and possibly the guinea pig. It is probable that the Amphibia also belong here, as well as teleostean fish. Most of the

insects belong to this group, with the exception of the Lepidoptera (moths and butterflies). In the Hymenoptera, however, another mechanism determines sex (see below). The roundworms (Nematodes) and sea urchins belong also to the XX-XO type.

The Avian Type (WZ-ZZ).

The other type of sex mechanism, the avian-moth type, is shown in the diagram (Fig. 118). The male has two like sex-chromosomes that may be called ZZ. These sepa-

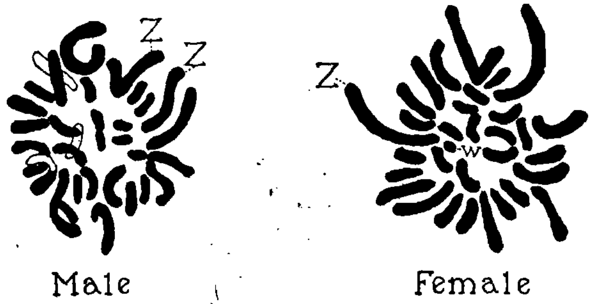


FIG. 119.

Male and female chromosome groups of the fowl. (After Shiwago.)

rate at one of the two maturation divisions and each ripe sperm-cell comes to contain one Z. The female has one Z-chromosome and a W-chromosome. When the eggs mature, each egg is left with one or the other of these chromosomes. Half the eggs contain a Z- and half contain a W-chromosome. Any W-egg fertilized by a Z-sperm produces a female (WZ). Any Z-egg fertilized by a Z-sperm produces a male (ZZ).

Here again we find a mechanism that automatically produces two kinds of individuals, females and males, in equal numbers. As before, a 1 to 1 sex-ratio results from the combination of chromosomes that takes place

at fertilization. The evidence for this mechanism in birds comes both from cytology and from genetics, although the former is as yet not entirely satisfactory.

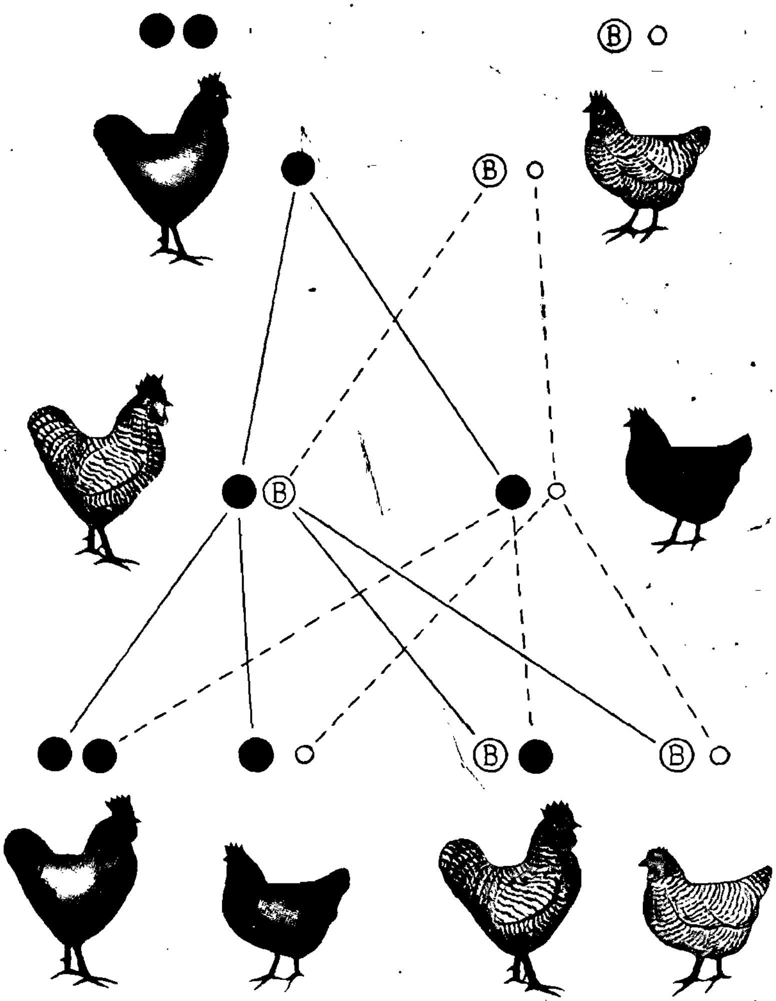


FIG. 120.
Diagram of cross between black and barred poultry, showing sex-linked inheritance.

According to Stevens, in the chick the male appears to have two large chromosomes equal in size (Fig. 119), presumably X's; the female has only one of these. Shiwago and Hance confirm these relations.

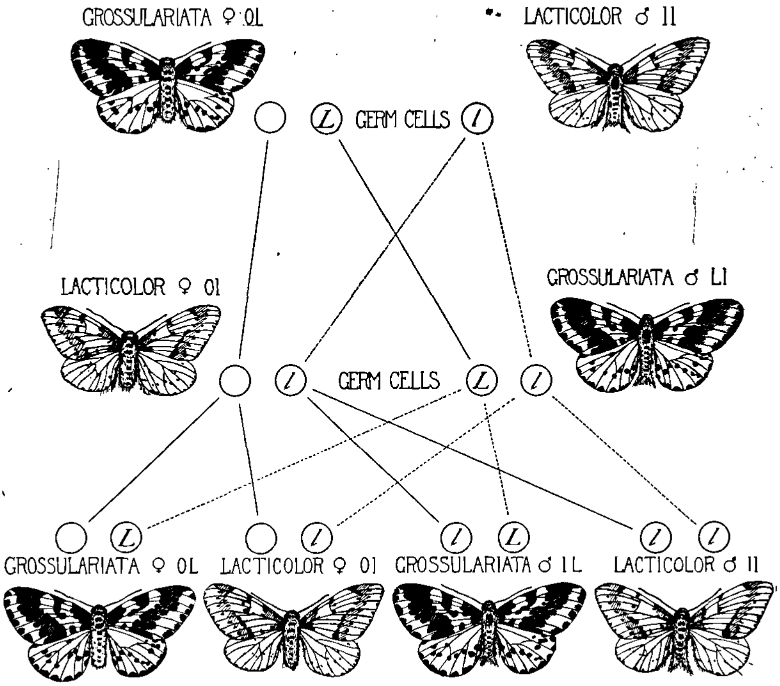


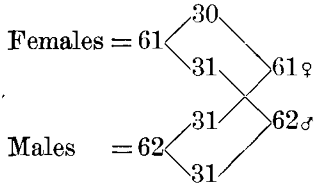
FIG. 121.
Sex-linked inheritance in the currant moth, Abraxas.

The genetic evidence for birds is beyond dispute. It comes from sex-linked inheritance. If a Black Langshan male is mated to a Barred Plymouth Rock female, the sons are barred, the daughters are black (Fig. 120). This is expected if the differential genes are carried by the Z-chromosomes, because the daughter gets her single Z-chromosome from her father. If the F_1 offspring are bred

lighter color, like the father; the sons a darker color, like the mother (Fig. 121). The daughter gets a single Z from her father; the son also gets this Z from his father, but another from his mother. This maternal Z carries the gene for darker color that is dominant, hence the darker color of her sons.

In the silkworm moth, Tanaka has found a sex-linked character, translucent skin of the larva, that is inherited as though carried in the Z-chromosomes.

In the moth Fumea casta there are 61 chromosomes in the female and 62 in the male. After conjugation of the chromosomes in the egg there are 31 chromosomes present (Fig. 122a). At the first polar division, when the first polar body is given off, 30 of the chromosomes (bivalents) divide and pass to opposite poles; the thirty-first single chromosome passes undivided to one or the other pole (Fig. 119b and b′). Half of the eggs will come to contain 31, half 30 chromosomes. At the next polar division all the chromosomes present divide, leaving each egg with the number it had before this division (*i.e.*, 31 or 30). In the ripening of the sperm of this moth, 31 bivalent chromosomes are present after conjugation of the chromosomes. At the first division the members of each pair separate and at the second each divides. Each spermatozoön carries 31 chromosomes. Fertilization of the eggs gives the following combinations:



In another moth, Talaeporia tubulosa, Seiler finds 59 chromosomes in the female and 60 in the male. In Soleno-

bia pineti an unpaired chromosome is not visible in the female or in the male, nor is an unpaired chromosome visible in several other moths. On the other hand, in Phragmatobia fuliginosa there is a compound chromosome containing the sex-chromosome. In the male there are two of these present; in the female only one is compound like those of the male. It seems not improbable that this relation may also exist in other moths where the W-element and the Z-elements do not appear as separate chromosomes.

Another demonstration of sex-linked inheritance in moths has been given by Federley in a cross between two species of moths (Pygaera anachoreta and P. curtula). This case is interesting because within each species the male and female caterpillars are alike. They show specific differences, however, when the caterpillars in the two species are compared. This specific difference, that is not dimorphic within the species, becomes the basis for a sexual dimorphism in the F_1 caterpillars (when the cross is made "one way"), because, as the results show, the main genetic difference between the caterpillars in the two races lies in the Z-chromosomes. When anachoreta is the mother and curtula the father, the hybrid caterpillars, after the first molt, are markedly different. The hybrid male caterpillars are closely similar to those of the maternal race (anachoreta), while the hybrid female caterpillars resemble those of the paternal race (curtula).

The reciprocal cross gives offspring that are all alike. These results are explicable on the assumption that the anachoreta Z-chromosome carries a gene (or genes) dominant to the gene (or genes) in the Z-chromosome of curtula. The special interest in this case is due to the genes in one species acting as a dominant to allelomorphic genes in the same chromosome of the other species. The analysis of the result can be carried over consistently

to the next generation, produced by back-crossing the F_1 male to either parent stock, provided, however, the triploid nature of the offspring be taken into account. (See Chap. IX.)

There are no grounds for supposing that the chromosomes involved in the XX-XY and in the WZ-ZZ types are the same. On the contrary, it is difficult to imagine how one type could change over directly into the other. There is no theoretical difficulty, however, in supposing that the change in balance that gives the two sexes may have arisen independently in the two types, even although the actual genes involved are the same or nearly the same in both.

Sex-Chromosomes in Dioecious Flowering Plants.

One of the surprises of the year 1923 was the simultaneous announcement by four independent workers that in some of the flowering plants with separate sexes a mechanism is present that follows the XX-XY type.

Santos found in the male of Elodea that 48 somatic chromosomes are present (Fig. 123), consisting of 23 pairs of autosomes and an XY unequal pair. At maturation the X and Y separate. Two kinds of pollen grains result, one with X, the other with Y.

Two other cytologists, Kihara and Ono, found in male plants of Rumex 15 somatic chromosomes consisting of 6 pairs of autosomes and 3 heterochromosomes (m_1, m_2, and M). These three come together at maturation of the germ-cells to form a group (Fig. 123). The M goes to one pole, the two small m's to the opposite. Two kinds of pollen grains result, 6a+M and 6a+m+m. The latter are male-determining.

Winge found an XY pair of chromosomes in two species of hops (Humulus lupulens and H. japonica). Nine

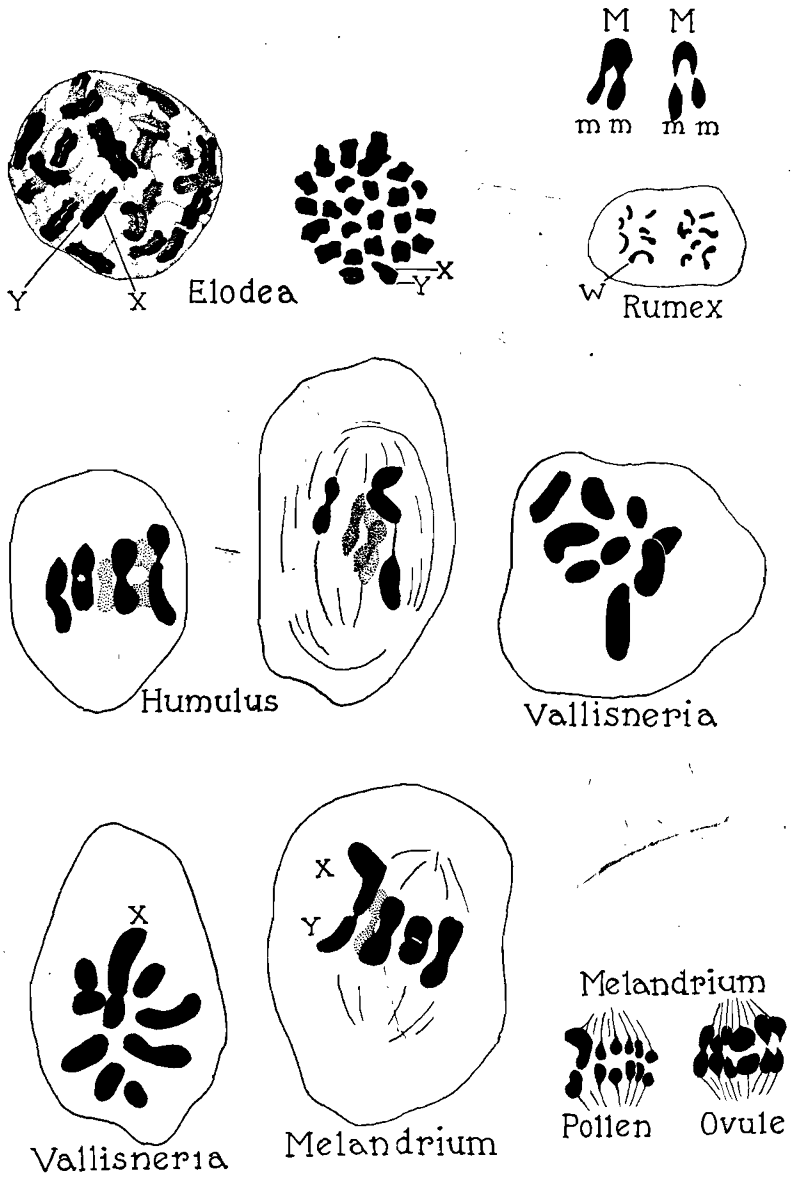


FIG. 123.
Maturation groups of several dioecious plants. (After Bělař.)

autosomes and an XY pair are present in the male. He also found in Vallisneria spirales that in the male there is an unpaired X-chromosome. The formula is 8a+X.

In Melandrium, Correns has concluded from breeding work that the male is heterogametic. Winge reported that the male formula is 22a+X+Y, which confirms Correns' deduction.

Miss Blackburn also reported an unequal pair of chromosomes in the male of Melandrium. She adds one all-important link to the chain of evidence. The female has two equal sex-chromosomes, one of them corresponding to one of the sex-chromosomes of the male (Fig. 123). At maturation they conjugate and reduce.

From this evidence we may, I think, safely conclude that some at least of the dioecious flowering plants make use of the same kind of mechanism for sex-determination that is present in many animals.

Sex-Determination in Mosses.

Several years before these observations on flowering plants had been made, it had been shown by the Marchals that when the spores are formed in dioecious mosses—mosses that have separate male and female gametophytes[1] (or sexual prothallia)—two of the spores derived from

[1] In mosses, ferns, and liverworts the haploid or gametophyte generation is spoken of as consisting of two sexes, male and female, and the diploid generation (sporophyte) as non-sexual or neutral. In flowering plants, the plant itself corresponds to the sporophyte of the mosses. It carries, as it were, the gametophyte generation within its pistil and stamens. A paradox arises from the use of the same terms male and female in mosses for one generation, that is, the haploid one, and for the alternative generation in flowering plants, that is, the diploid. The paradox is not so much a question of diploid and haploid (this contrast is encountered even within the same generation in some animals—bee, rotifers, etc.), but in using the same terms for contrasted generations, one sexual, the other non-sexual. With this understanding, however, no serious difficulty arises by following conventional usage.

the same sporophyte mother cell produce female gametophytes and the other two male gametophytes.

Somewhat later Allen discovered in the nearly related group of liverworts (Fig. 124) that in the haploid female

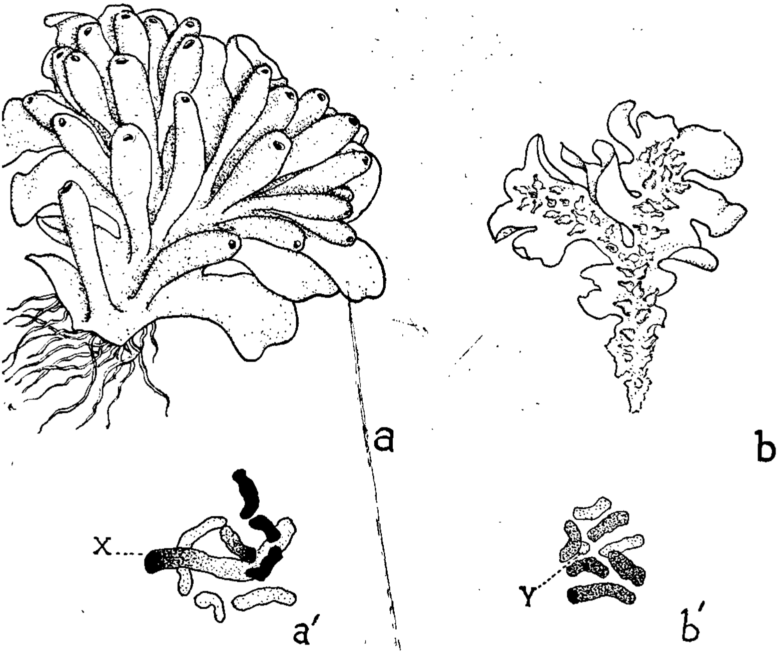


Fig. 124.

a, Female and b, male prothallia of liverwort. The female with one large X-chromosome, a'; the male with one small Y-chromosome, b'. (After Allen.)

prothallium (gametophyte), with eight chromosomes, there is one (X) that is much larger than the other seven chromosomes; and in the haploid male prothallium (gametophyte), with eight chromosomes, one (Y) is much smaller than the other seven (Fig. 121b'). Each egg will

contain an X-, and each sperm a Y-chromosome. After fertilization the sporophyte will have 16 chromosomes (including one X and one Y). When the spores are formed, reduction takes place, the X and the Y separating. Half of the haploid spores so formed will contain an X and give rise to a female prothallium, and half will contain a Y and give rise to a male prothallium.

More recently still, Wettstein has made some critical experiments with dioecious mosses, experiments that carry the analysis further. By utilizing a discovery of the Marchals, he produced gametophytes that contained both the male and the female groups of chromosomes (Fig. 125 to the left). For example, following the Marchals' method, he cut off pieces of the spore-bearing stalk (whose cells are diploid). From the fragment a gametophyte developed, also diploid. In this way he obtained FM gametophytes.

Then in another way he made diploid male and female moss plants that were double females (FF) and double males (MM). This was accomplished as follows:

By treating the protonema threads with chloral hydrate and other drugs and reagents, he brought about the suppression of a cell division in an individual cell after the chromosomes had already divided. In this way he could produce in these dioecious species, diploid giant cells that were doubled in their female or else in their male elements, chromosomes, for example. From such a diploid cell a protonema or moss plant was produced. By artificial means Wettstein then brought about several new combinations, some triploids, others tetraploids. Some of the most interesting of these combinations are shown in the diagram (Fig. 125, to the right).

A diploid cell from a *female* thread gives a diploid moss plant, FF, that produces diploid egg-cells. Similarly an MM plant is produced from a diploid *male* thread.

Vhen an FF egg and an MM sperm are brought together tetraploid sporophyte (FFMM) is produced.

When the FF ovule is fertilized by a normal male

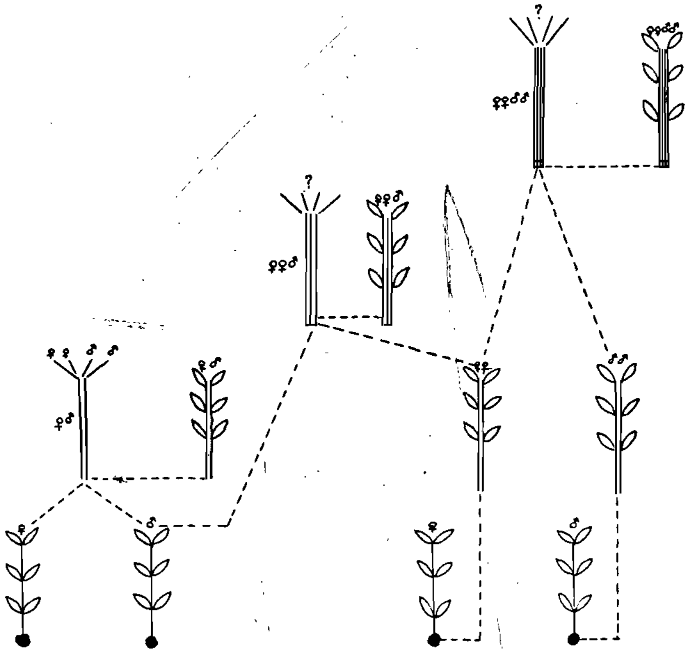


FIG. 125.

Diagram illustrating different combinations of diploids and triploid mosses. (After Wettstein.)

perm cell M, a triploid sporophyte (FFM) is produced. hus:

```
M          FF           MM
  \       /   \        /
    FFM          FFMM
```

rom each sporophyte, FFM and FFMM, a gametophyte an be regenerated. Each of these plants develops both

male and female elements, and both produce eggs and sperm-cells; but the number of female organs (archegonia) and of male organs (antheridia) and their time of appearance show characteristic differences.

The Marchals had obtained, as has been said, the diploid FM gametophyte in the same species used by Wettstein, and had shown that it produces both female and male organs. Wettstein confirms this and reports that the male organs develop before the female.

A comparison of the three types, FM, FFM, FFMM, is interesting. The FM plant is strongly protandric. At first there is a great excess of antheridia or male organs compared with archegonia. The archegonia develop later.

The FFMM plant is, as Wettstein says, twice as strongly protandric as the FM plant. At first only antheridia appear. Very late in the year, when the old antheridia have gone, a few young archegonia appear—some plants never develop them. Still later a vigorous development of female organs may set in.

The triploid plants are protogynic. At least, at the time when the FFMM tetraploid plants have only male organs (in July), the triploids have only female organs. Later (in September) both organs are present.

These experiments are interesting in showing how artificial hermaphroditic individuals may be made from plants that normally have separate sexes by combining the two sets of elements. The results also show that the sequence in which the sexual organs develop is determined by the age of the plant. More important is the actual reversal of this time relation by changing the genetic composition in the opposite direction.

CHAPTER XV

OTHER METHODS OF SEX-DETERMINATION INVOLVING THE SEX-CHROMOSOMES

THE determination of sex through the redistribution of the sex-chromosomes in the germ-cells is regulated in some animals in other ways than those described in the preceding chapter.

FIG. 126.

Separation of the two small X-chromosomes from the autosomes in Ascaris eggs. (After Geinitz.)

The Attachment of the X-Chromosomes to Autosomes.

The attachment of the sex-chromosomes to other chromosomes, that is known to occur in a few forms, tends to conceal the differential character of X- and Y-chromo-

somes. Their presence has been detected, in such cases, by their occasional separation, as in Ascaris (Fig. 126), from their attachment, or by the differential staining properties of the X-chromosome in the male, or, as in certain moths studied by Seiler, by the regular separation of the compound chromosome into its components in the somatic cells of the embryo.

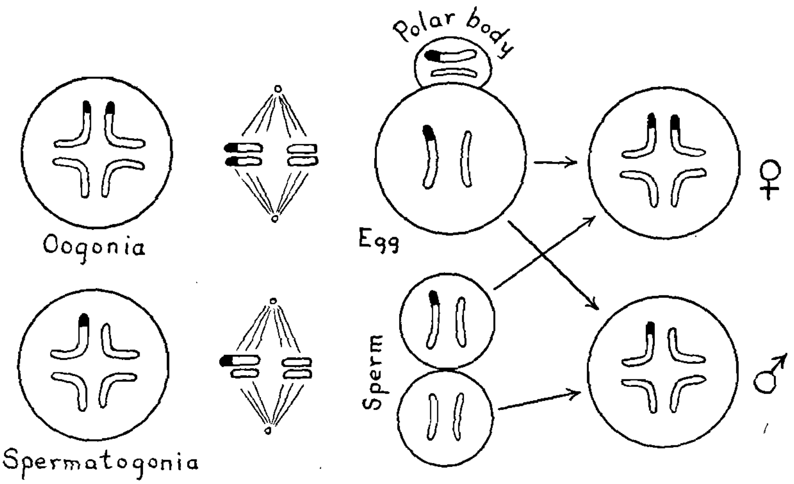


FIG. 127.

Diagram illustrating the distribution of the attached X-chromosomes in the male and female of Ascaris. (After Boveri.)

The attachment of the sex-chromosomes to ordinary chromosomes, or autosomes, as they are called, involves the mechanism of sex-linked inheritance, more particularly should crossing-over take place in the male between the autosome attached to the X and its mate lacking the attached X. An example will illustrate the point at issue. In Fig. 127 the X-chromosomes of Ascaris are indicated by the black ends of those chromosomes to which they are attached. In the female there are two X-chromosomes,

each attached to a member of the same pair of autosomes. In the mature egg one such compound chromosome (therefore one X) is left in each egg. In the male, one X is present, attached to the corresponding autosome, but the other autosome has no attached X. After maturation half of the sperm-cells will contain an X, half will be without an X. The mechanism for sex-determination is obviously here the same as in the XX-XO type.

In the female, crossing-over might take place both between the two X-chromosomes and between the two attached autosomes. But in the XO male the situation would be different; for in the male the X part of the compound chromosome has no opposite, hence no crossing-over is expected in that part. This would insure the coherence of the sex-differentiating genes and of the sex-mechanism; but between the autosomal parts of the compound chromosome an interchange might then take place without affecting the sex-mechanism. The characters whose genes lie in the X-component will show sex-linked inheritance, *i.e.,* the recessive character, will appear in the sons. The recessive characters whose genes are in the autosomal part will not appear in the sons. However, the character whose genes are in the autosomal part will show partial linkage to sex and to the characters whose genes lie in the X-component.[1]

In the imaginary example just given, the autosome without an attached X, that is, the mate of the compound chromosome with an X in the male, will appear to correspond to the Y-chromosome of the ordinary XX-XY type

[1] According to McClung the X-chromosome in the male of Hesperotettix is not constantly attached to the same autosome, although in a given individual its attachment is constant. In other individuals it may be free. Were sex-linked characters known in such a type, their inheritance might be complicated by this inconstant relation of the X-chromosome to the autosomes.

(because it is confined to the male line), except, as just pointed out, that it carries genes that are like those in the corresponding part of the compound X-chromosomes. Cases of inheritance have, in fact, been recently recorded where certain genes appear to be carried by the Y-chromosome, and such cases have been interpreted to mean that the Y-chromosome itself may sometimes carry genes.

There is no objection to such a statement if interpreted as above, but there is an obvious objection to this statement if it is intended to mean more than this; for the chromosomal sex-mechanism would break down if the X and the Y of the male interchanged throughout. If this happened, the two chromosomes would after a time become identical, and the difference in balance that gives males and females would be lost.

The Y-Chromosome.

There are two groups in which the genetic evidence has been interpreted to mean that Mendelian factors may be carried in the Y-chromosome. In fish, belonging to two different families, it has been shown by Schmidt, Aida, and Winge that the Y carries genes. In the gypsy moth Goldschmidt has interpreted the result of species-crosses in the same way (here the W-chromosome). The latter results will be considered in the chapter on sex intergrades; the former may now be taken up.

In the small aquarium fish, Lebistes reticulatus, a native of the West Indies and northern South America, the males are highly colored and strikingly different from the females (Fig. 128). The females in different races are closely similar to each other, while the males show characteristic differences in color. Schmidt has found that when a male of one race is bred to a female of another race, the sons are like the father. If these hybrids (F_1) are inbred, their sons (F_2) are again all like the father,

and none of them show any characters of males of the maternal grandmother's race. The F_3 and F_4 males are again all like those of the paternal forefather. There seems to be here no Mendelian splitting for any characters that might have been expected to have come through the maternal grandparent.

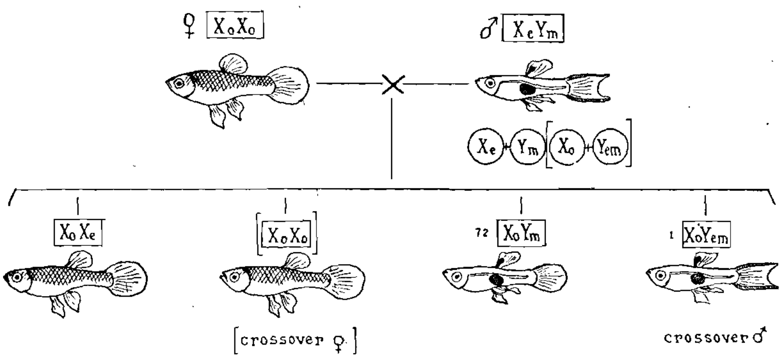


Fig. 128.

Diagram illustrating the inheritance of a sex-linked character in fish, carried both by the X- and the "Y-chromosome." (After Winge.)

The same results are obtained when the reciprocal cross is made; the sons and grandsons are all like the paternal parent, etc.

In another fish, Aplocheilus latipes, inhabiting small streams and paddy fields of Japan, several types differing in color are found. Other types have also appeared in cultures. In these fish both males and females of each type occur. Aida has shown that several of these differences are transmitted through the sex-chromosomes (both X and Y). The genetic transmission of these characters can be explained on the hypothesis that the genes are carried sometimes in the Y- and sometimes in the X-

chromosomes, and that crossing-over between these chromosomes may take place.

For example, the character, white body color, is sex-linked in inheritance. Its allelomorph is red body color. When a pure white female was mated to a pure red male, the sons and daughters (F_1) were all red. When these were inbred they gave,

Red ♀	Red ♂	White ♀	White ♂
41	76	43	0

Assuming that the genes for white are carried in the two X-chromosomes of the female and designating such a chromosome by X^w (Fig. 129), and assuming that the

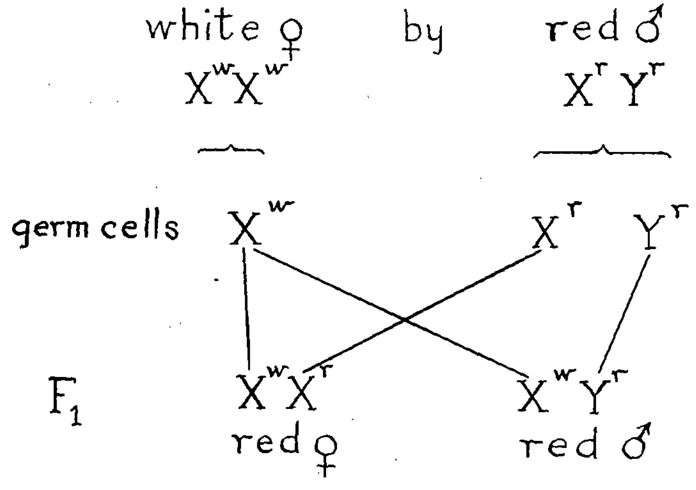


FIG. 129.

Diagram showing the inheritance of a character whose gene is carried by the "Y-chromosome," as well as by the X-chromosome.

gene for red is carried both by the X and the Y of the male, and designating these by X^r and Y^r, the cross given above works out on the XX-XY formula as shown in Fig. 129. If red (r) dominates white (w), both sons and daugh-

ters (F_1) will be red. If these are inbred the results are shown in the next diagram (Fig. 130). White and red daughters in equal numbers are expected and red sons only, that are equal in number to the sum of the two female classes.

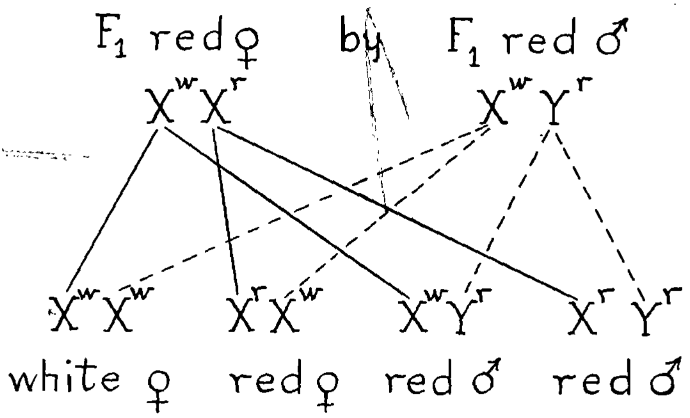


FIG. 130.

Diagram illustrating the inheritance of red and white color from two F_1 heterozygous male and female fish. The Y-chromosome as well as the X may carry the gene for red (r).

Thus from a red male and a white female no white grandsons are expected on this formulation unless in an $F_1X^wY^r$ red male, crossing-over between X and Y occurs to give a Y^w chromosome (Fig. 131). When such a chromosome meets an egg-carrying X^w, a white male, X^wY^w, will be produced. A white male appeared, in fact, in one experiment in which an F_1 heterozygous red male, X^wY^r (obtained in the above experiment), was back-crossed to a pure white female. The results obtained were:

Red ♀	White ♀	Red ♂	White ♂
2	197	251	1

The occurrence here of two red ♀'s and one white male may be accounted for, if, in the F_1 ♂ (X^wY^r), an interchange occurred about once out of 451 times, as shown in Fig. 131. Similar results were obtained when white and brown males were crossed, but no cross-overs were recorded. When variegated red females and white males were crossed, the same kind of results were obtained with 11 cross-overs out of 172 individuals in the back-cross.

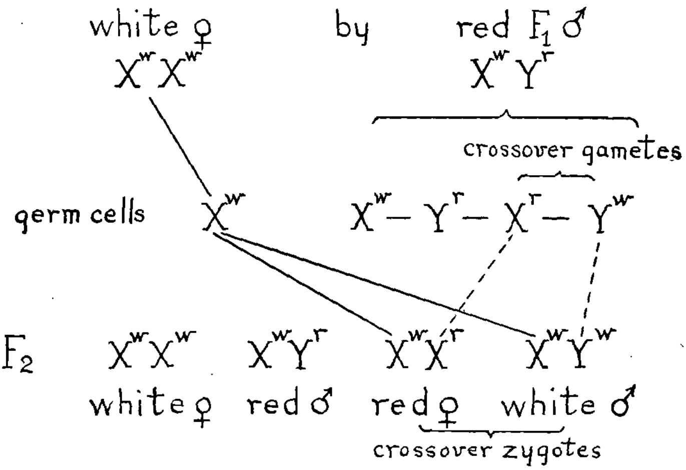


FIG. 131.

Diagram illustrating crossing-over between genes for red and for white carried by the X- and "Y-chromosome" of an F_1 male fish. These genes are interpreted as allelomorphs.

Winge (1922-1923) extended Schmidt's experiments with Lebistes, and independently reached the same conclusions concerning the Y-chromosomes as had Aida. The results of a cross between a female of one race, X_oX_o, and a male of another race, X_eY_m, are shown in Fig. 128. The ripe germ-cells of this heterozygous male are represented by two non-cross-over classes, X_e and Y_m, and two cross-over classes, X_o and Y_{em}. Correspondingly there were two

kinds of males, X_oY_m and X_oY_{em}. The latter are rare, one out of 73 sons.[2] Whether crossing-over also occurs in the female cannot be determined from Winge's data, since he gives no cases of X_eX_m females. Moreover, he represents one type of female as X_o and implies that the X_o-chromosome is lacking in certain genes. Two pairs of genes are necessary to show crossing-over when two X's are present. In fact, Winge represents an X_e that has crossed over to a Y_m as X_o without representing the reciprocal allelo-

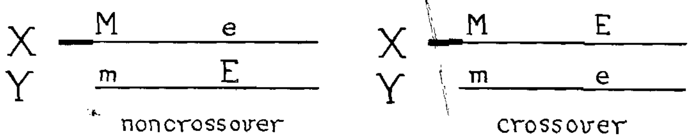


FIG. 132.

Diagram illustrating the possible relations of an attached X-chromosome to crossing-over between the autosomal portion of this compound chromosome and the autosome (the male of the latter) here called Y.

morphic change. The full formula should represent one of the X's containing the genes M and e, and the Y, in this case, as containing the genes m and E. After crossing-over the X would then contain E and M and the Y would contain e and m, as shown in Fig. 132. The X-chromosome after crossing-over is not X_o, but X_{ME}, and the Y-chromosome Y_{me}. If m and e are dominant over M and E, the results would be as recorded, except that another cross-over is expected, namely, X_{ME}. If the part of the X to the left of the M contains the sex-determining genes (the heavier part of the X in the figure) the absence of this cross-over in the experiment might be explained as due to the proximity of M to the X-component.

In a later paper Winge (1927) has reported nine genes

[2] In another experiment 4 cross-overs out of 68 sons are recorded.

in the Y- and three in the X-chromosomes of Lebistes, that have, as yet, shown no crossing-over. He suggests that this is either because they are close to the male-determining gene in the Y-chromosome, or else that they are identical with the male-determining gene. Five other genes show crossing-over between the X and Y, and one gene is autosomal. He represents the male-determining gene as single and dominant and leaves open the question of the nature of the allelomorph in the X-chromosome, labeling it zero.

Degeneration of Male-Producing Sperm.

In two closely related families of bugs, the Phylloxerans and Aphids, belonging to the XX-XO type, the male-producing class of sperms (no X) degenerate (Fig. 133). This leaves only the female-producing sperms (X). The sexual egg (XX), after extrusion of two polar bodies, is left with one X-chromosome. Fertilized by the X-sperm, these eggs produce only females (XX). These females are called stem mothers. They are parthenogenetic and become the starting point of a succession of other parthenogenetic females. After a time, some of these females may produce male offspring, others producing sexual females. The latter are diploid, like their mothers, but in them the chromosomes conjugate and their number becomes reduced to half. The former individuals that produce males do so by a process that will be described in the next section.

The Elimination of One X-Chromosome from a Diploid Egg to Produce a Male.

In the Phylloxerans, as stated above, a certain kind of female appears near the end of the parthenogenetic cycle whose eggs are a little smaller than those of the earlier females. Just before maturation of the smaller eggs the

X-chromosomes come together (there are four X's present). Two of them pass out of the egg into the single polar body that is given off (Fig. 134). The autosomes at this time divide, and half of each is eliminated. The

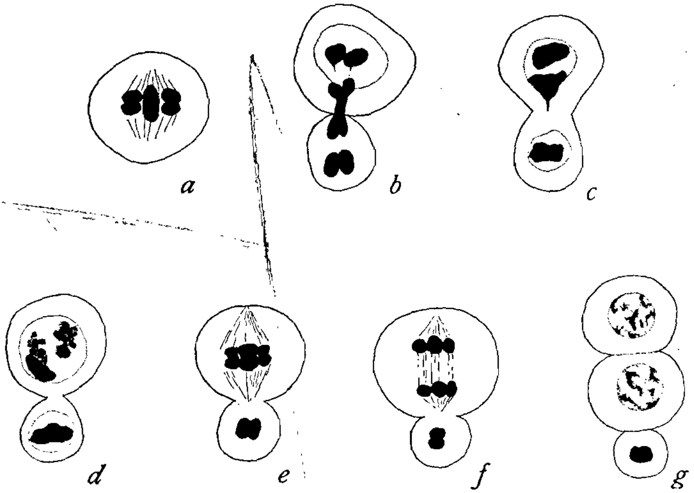


FIG. 133.

First maturation division of the bearberry aphid. At the first division, *a-c*, the large X-chromosome passes into one cell. At the second division, *e*, *f*, *g*, this cell divides again producing two functional female-determining sperms. The rudimentary cell does not divide again.

egg is left with a diploid set of autosomes and half of the X-chromosomes. It develops, by parthenogenesis, into a male.

In the Aphids a similar process takes place. The actual extrusion of one of the X's from the egg (there are only two X's present) has not been observed, but since, after the single polar body is given off, there is one less chromosome present in the egg, there can be no doubt but that one is lost, as in the Phylloxerans.

In these two groups the male sex is determined by a

different process from that which takes place in other insects, but the same mechanism is utilized in a different way to bring about the same end-result.

There is one further fact of unusual interest in this case. In the Phylloxerans the female that gives rise to the male eggs—she is called the male-egg producer—forms smaller eggs than did her parthenogenetic forbears. The

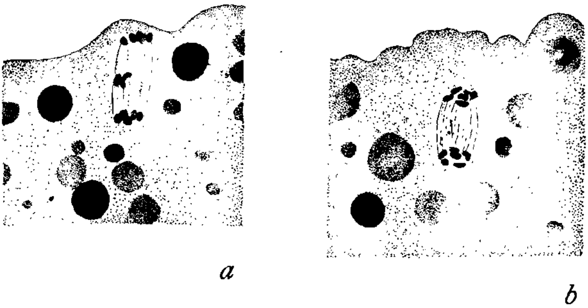


FIG. 134.

a, The first polar spindle of a "male egg" of Phylloxera in which two chromosomes lag on the spindle and are ultimately thrown out of the egg, leaving five chromosomes in the egg nucleus. *b*, The first polar spindle of a female egg, in which all six chromosomes divide leaving six chromosomes in the egg nucleus.

fate of the eggs is, therefore, indicated before the X-chromosomes are eliminated from them. It might appear that, here, sex is determined by the size of the egg, which might mean the amount of cytoplasm contained in it; but the conclusion is an illegitimate inference from the evidence, since the egg becomes a male only after half of its X-chromosomes are eliminated. What would happen if they were retained we do not know—probably the egg would develop into a female. At any rate, we have here an instance of a change that has taken place in the mother that leads to the formation of the smaller egg, which, in turn, reduces the number of its X-chromosomes to pro-

duce a male. The nature of the change in the mother is unknown at present.[3]

Sex-Determination through the Accidental Loss of a Chromosome in Spermatogenesis.

In hermaphroditic animals no sex-determining mechanism has been found, and none is expected, since all the individuals are alike, each with an ovary and a testis. In

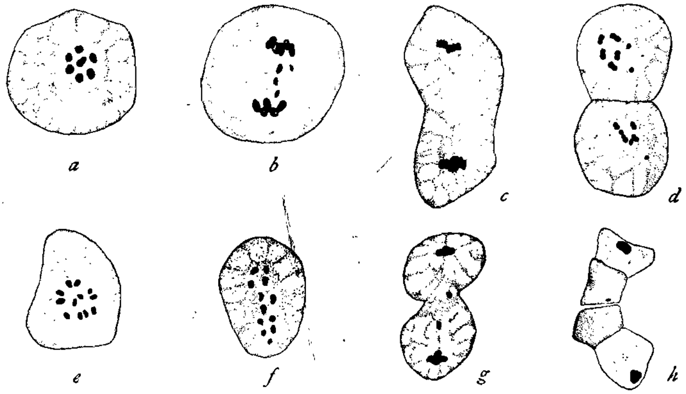


FIG. 135.

First and second maturation division of the sperm-cell of Angiostomum nigrovenosum. At the second division (lower line) one of the X-chromosomes gets caught in the division-plane. (After Schleip.)

one species of nematode worms, Angiostomum nigrovenosum, there is an hermaphroditic generation that alternates with a generation consisting of males and females. Boveri and Schleip have shown that when the sperm-cells mature in the parthenogenetic generation (Fig. 135) one

[3] In one of the worms, Dinophilus apatris, eggs of two sizes are produced by each female. Both kinds give off two polar bodies, resulting in a haploid pro-nucleus. Both kinds of eggs are fertilized; the larger egg produces females, the smaller one males (Nachtsheim). At present the cause of the production of two kinds of eggs in the ovary is entirely unknown.

of the X-chromosomes frequently gets lost (being caught in the division plane) and this leads to the production of two classes of sperm, with five and six chromosomes. In the maturation of the eggs of the same female the

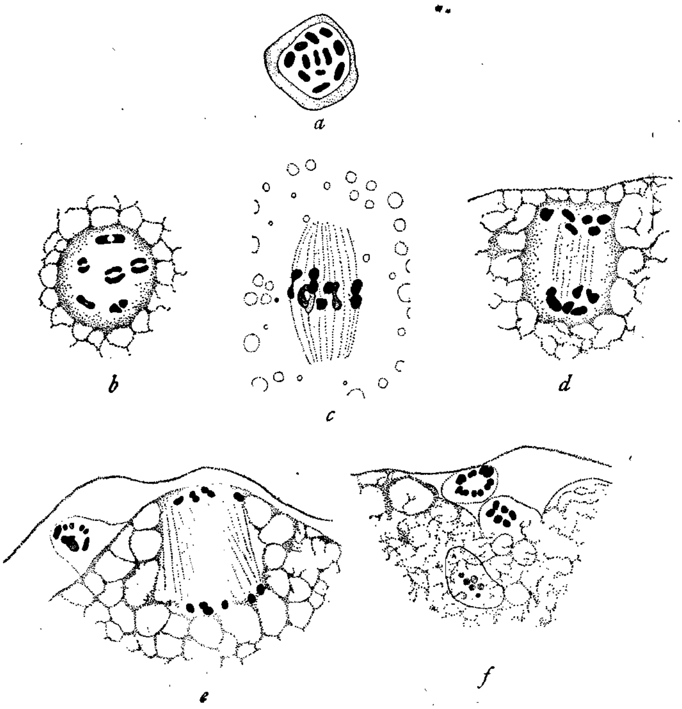


FIG. 136.

The two maturation divisions of the egg of Angiostomum nigrovenosum. Six chromosomes are left in the egg nucleus. (After Schleip.)

twelve chromosomes conjugate, giving six gemini (Fig. 136). At the first maturation six go into the first polar body and six remain in the egg. These split and six daughter chromosomes go into the second polar body, leaving six chromosomes in the egg, each with one X-chromosome. An egg fertilized by a sperm with six chromosomes

produces a female; an egg fertilized by a sperm with five chromosomes produces a male. Here an accident in cell-division becomes the mechanism of sex-determination.

Diploid Females and Haploid Males.

In the rotifers there is, first, a long series of generations of parthenogenetic females with the diploid number of chromosomes. No reduction takes place in the eggs and one polar body is given off. The series may apparently continue indefinitely under certain conditions of nourishment. The series can, however, as shown by Whitney, be brought to an end by a change in diet—such as feeding the females on a green flagellate. A female feeding on such a diet now produces daughters (by parthenogenesis) with dual possibilities. If one of these daughters is fertilized by a male (that may have then appeared), each egg, before maturation, is entered by a single sperm. The egg enlarges in the ovary and a thicker shell is laid over it (Fig. 137). It gives off two polar bodies, and then the sperm nucleus (haploid) unites with the haploid nucleus of the egg, restoring the full number of chromosomes. This egg is a resting or winter egg. It contains the diploid set of chromosomes, and after a time develops into the stem mother of a new line of parthenogenetic females, etc.

On the other hand, if the female in question is not fertilized, she produces eggs that are smaller than the ordinary parthenogenetic eggs. The chromosomes conjugate, and two polar bodies are given off. The egg is left with a haploid set of chromosomes. It segments, without doubling the number of its chromosomes, and produces a male. It is not clear what happens during the formation of the spermatozoa in the haploid males. Neither Whitney's (1918) nor Tauson's (1927) work gives a convincing account of the changes that take place.

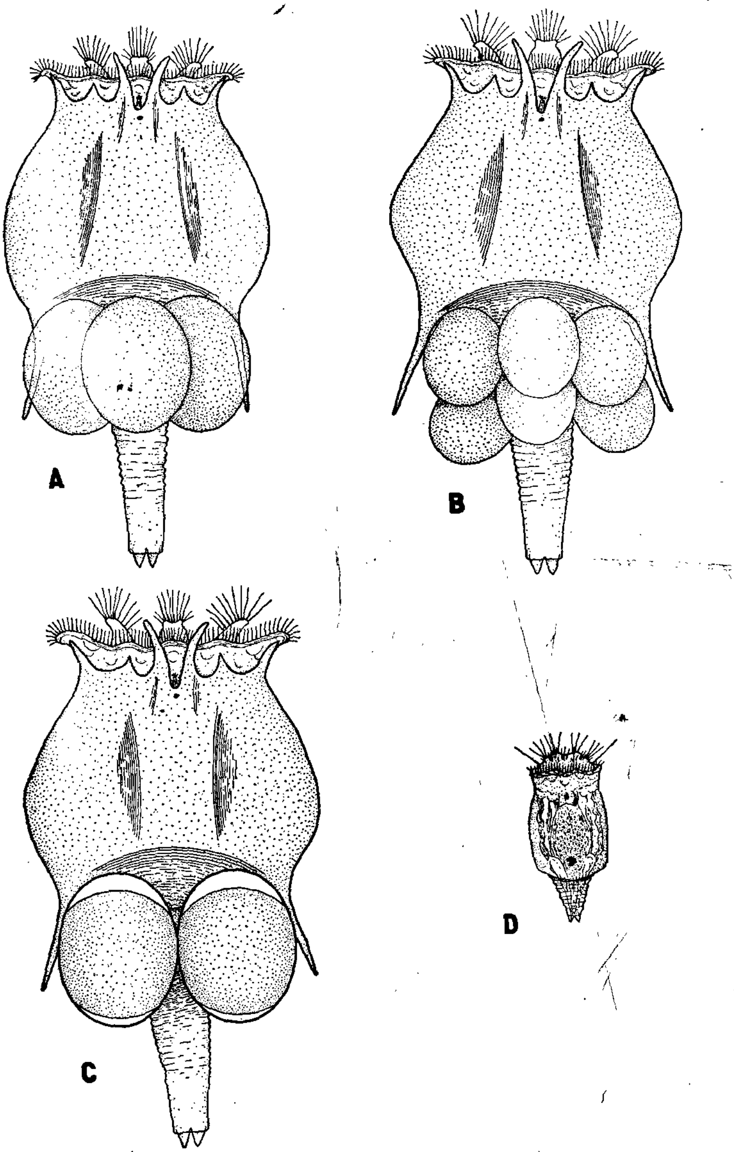


FIG. 137.

The rotifer, Brachionus bakeri. A, female with attached parthenogenetic female-producing eggs. B, female with attached parthenogenetic male-producing eggs. C, female with attached sexual eggs. D, male. (After Whitney.)

The evidence, taken at its face value, appears to mean that the haploid number of chromosomes produces a male, the diploid a female. The presence of sex-chromosomes is nowhere apparent, hence the presence of specific sex genes cannot be assumed. Even if the absence of such genes be granted, it is not apparent why the half number of chromosomes should produce a male and the diploid number a female, unless the differential factor here involved be the relation between the amount of cytoplasm in the two kinds of eggs and the number of chromosomes present. Even then, however, the result is difficult to bring into accord with the case of the bee (described below), where the diploid egg, that produces a female, and the haploid egg, that produces a male, have the same size. The outstanding fact in both cases is that the haploid number of chromosomes is correlated with the male sex, even although something else determines in the rotifer which eggs become haploid.

It might be possible to invent an explanation involving sex-chromosomes if two kinds of X-chromosomes were postulated and if, at the reduction division, one passes out into the polar body of the male egg and the other one from the sexual egg (both being retained in the parthenogenetic egg); but it must be confessed that at present there is no excuse or need perhaps for advancing such a speculation.

Sex-determination in bees, and in their near relatives, the wasps and ants, is also connected with the diploid and haploid condition of the nuclei. The facts seem well established, but the interpretation here is also obscure. The queen bee deposits eggs in the queen-cells, in the worker-cells, and in the drone-cells. These eggs are, before being laid, all alike. The eggs in the worker-cells and the queen-cells are fertilized at the time of deposition; in the drone cells the eggs are not fertilized. All eggs give off two

polar bodies. The egg nucleus is left with the haploid number of chromosomes. In the fertilized eggs the sperm brings in a haploid set of chromosomes, which, uniting with the egg nucleus, gives the diploid number. From these eggs females develop (queens or workers). The queens owe their more complete development to the food supplied to the larvae in the queen-cells. This food is different from that given to the larvae in the worker-cells. The males (drones) are, as has been said, haploid.[4]

In this case, the determination of sex cannot be supposed to be due to any effect preceding maturation. There is no evidence that the presence of the sperm-nucleus in the egg affects the way in which the maturation division of the chromosomes takes place. Furthermore, there is no evidence that the environment (drone-cell or worker-cell) has any effect on the course of development. There is, in fact, no evidence here that any particular set of chromosomes has been set apart as sex-chromosomes. The only known difference between the two kinds of individuals, females and males, is the number of chromosomes present. We can, at present, only fall back on this relation as the one that is in some unknown way correlated with sex-determination. At present it cannot be satisfactorily brought into line with other cases in insects, where sex is related to a balance between genes in the chromosomes, but it may still be due to a balance between the chromosomes (genes) and the cytoplasm.

There is one further fact that involves sex-determina-

[4] It is known that, as the cleavage of the unfertilized egg of the male proceeds, each chromosome breaks into two parts (except possibly in the nuclei that pass into the germ-track). This process does not appear to be a "division" of each chromosome, but rather its breaking or separating into two pieces. If this interpretation is correct there is no actual increase in the number of the genes and the occurrence of this process (also known in some of the nematodes) does not throw any light on the question of sex-determination.

tion in bees. When the maturation of the germ-cells in the male takes place, the first division is abortive. A small cell is pinched off without chromosomes (Fig. 86). At the second division the chromosomes divide. Half pass into one cell, that is very small and later degenerates; half remain in the larger cell, that becomes the functional spermatozoön and contains the haploid number of chromosomes. This number it brings into the egg, which, as stated, then develops into a female.

There are a few cases on record (Newell) where two races of bees have been crossed and the progeny of the hybrid recorded. The males are said to show the characters of one or the other original race. This is expected, in so far as the two races differ in genes in one and the same pair of chromosomes, because these would be separated at reduction, and one or the other would be retained in the haploid egg that produces a male. But if the racial differences depend on genes lying in different pairs of chromosomes, no such sharp distinction into two classes of grandsons is to be expected.

The worker bees (and ants) occasionally lay eggs. These become males, as a rule, which is expected, since the workers cannot be inseminated by the drones. There are records in ants of the rare appearance of sexual females from workers' eggs. It may be supposed that this is due to the retention of a double set of chromosomes. In the "Cape bees" the production of females (queens) from workers' eggs is said to be a common occurrence. Provisionally we may apply the same explanation as that given above for the females of worker ants that rarely produce eggs some of which, under special conditions, develop into females.

The direct transmission of the characters of the mother to her haploid sons has been more completely demonstrated in Whitings' work on the parasitic wasp, Habro-

bracon. The common type has black eyes. A mutant male with orange eyes appeared in the cultures. Crossed to black-eyed females, there were produced by parthenogenesis 415 black-eyed sons, and from fertilized eggs 383 black-eyed daughters.

Four of these (F_1) daughters, when isolated, produced parthenogenetically 268 black-eyed males and 326 orange-eyed males and no females.

Eight other F_1 daughters (from the original orange male) were mated with their F_1 brothers. There were produced 257 black-eyed sons, 239 orange-eyed sons, and 425 black-eyed daughters.

The original mutant orange-eyed male, when bred to his F_1 daughter, gave 221 black males, 243 orange males, 44 black females, and 59 orange females.

These results are expected on the hypothesis that the male is haploid and comes from an unfertilized egg. The gene for orange eyes and that for black eyes separate in the germ-cells of the hybrid mother when her germ-cells mature, half of the gametes then have one kind of gene, half the other kind. Any pair of genes in any pair of chromosomes will give the same result.

The reciprocal cross was also made, namely, an orange female was crossed to a black male. Eleven such matings gave 183 black daughters and 445 orange males, as expected; but twenty-two matings gave, in addition to 816 black females and 889 orange males, *57 black males.* The occurrence of these black males calls for a different explanation. They have obviously come from eggs fertilized by a black-producing sperm. A possible explanation would seem to be that the haploid sperm-nucleus has developed in the egg, and has given rise to those parts from which the eyes at least have come. The rest of the egg might then get its nuclei from the haploid egg-nucleus. There is, in fact, some evidence that this is the correct

explanation, since Whiting has shown that some of these exceptional black males may breed as though all their sperm carried only the orange gene of the mother. But there are other facts indicating that in these cases the explanation is not so simple as this, for most of the black males are sterile, as well as the few daughters arising from those males that are fertile (the mosaic males).[5] Whatever the final solution may be for these exceptional cases, the main results of the crosses confirm the theory that the males are haploid.

Sex in Haploids.

The demonstration by Allen in 1919, that the cells of the female haploid gametophyte of the liverwort, *Sphaerocarpus,* have a large X-chromosome and that the cells of the male haploid gametophyte have a corresponding small Y-chromosome, gives a reasonable explanation of the differences shown by their prothallia (gametophytes). Similarly the experimental demonstration by the Marchals, by Wettstein and others that from each spore-mother-cell of dioecious mosses two spores arise that develop into female protonemata (gametophytes), and two other spores that develop into male protonemata (gametophytes), falls into line with Allen's results on the allied liverworts. It is customary to speak of the two kinds of gametophytes as female and male respectively since one produces eggs the other sperm cells (antherozoids). The

[5] According to Anna R. Whiting (1925), "the black-eyed patroclinous males show a higher percentage of morphological abnormalities than do males and females normally produced. The majority of patroclinous males tested have been sterile, some have bred as blacks and been partially fertile, while a few mosaics have produced orange-eyed daughters and have been fully fertile. The orange-eyed daughters of patroclinous males are normal in morphology and fertility. The black-eyed daughters of patroclinous males are few in number and show a large percentage of abnormalities and are almost completely sterile." The exceptional males in Hadrobracon may explain some of the anomalous cases that have been recorded in honey bees.

succeeding generation, the sporophyte (zygote) arising from the fertilization of the egg by the sperm, is sometimes said to be sexless or asexual. It has however one X- and one Y-chromosome.

Some unnecessary confusion has arisen between the terminology used for the moss and liverwort and that employed for dioecious flowering plants in which the terms female and male apply to the sporophyte (diploid) generation and not to the egg-cell (which is part of the haploid generation within the embryo sac) and to the pollen grain (which is also part of the haploid generation). It may seem at first sight, that male and female are used in these two groups in a different sense. There is no real contradiction, however, except a verbal one arising from phylogenetic implications. If the two cases in question are stated in terms of genes, the imagined difficulties disappear. In the liverworts, for instance, the balance of genes in the haploid gametophyte, containing the large X-chromosome, leads to the production of egg-cells and the balance of genes in the haploid gametophyte containing the small Y-chromosome leads to the production of sperm-cells. The egg-bearer is here called female, the sperm-bearer male. In the diploid generation of those flowering plants that are dioecious, where a differential pair of chromosomes is present in the male, the balance of the genes in the diploid generation between the autosomes and two X's gives a female (an individual that produces eggs), and the balance of the genes in the diploid generation between the autosomes and the XY pair gives a male (an individual that produces sperm-cells). Both in the liverwort and the flowering plant the situation turns on a balance between sets of genes. It may be that the same sets of genes are not involved in both cases, or that some of them are the same, others are different. The essential point is that in both cases, differences in balance lead to two kinds of indi-

viduals which are called females and males since they produce eggs and sperm-cells respectively.

In criticism of these statements it may possibly be said that the facts have only been restated and not explained. This is quite true. All that has been attempted is to point out that the facts may be restated in such a way that there is no apparent contradiction involved in the two cases. We may look forward perhaps to the time when the number and nature of the genes involved in cases where a difference of balance produces two kinds of individuals, will be determined. Meanwhile there is nothing in the situation that need cause anxiety, and certainly nothing that can be used as a refutation of recent advances in an understanding of sex-determination.

The haploid condition in animals is characteristic of the gametes. There are no cases of alternating haploid and diploid generations as in plants. But there are two or three types at least in which one sex is diploid and the other haploid. In the Hymenoptera and a few other insects the female is diploid and the male haploid, at least in the early stages of development. In Rotifera the females are diploid and the males are haploid. There is no evidence in either group of sex-chromosomes as such. At present no explanation resting on experimental evidence can be offered to explain these relations. Until such evidence is forth-coming the possible theoretical interpretations that have been suggested are not illuminating.

In *Drosophila* on the other hand where a known sex mechanism is at hand, and where there is experimental evidence bearing on the problem of balance of the genes involved in sex-determination, there is a recent observation by Bridges that is significant. Two mosaic individuals were found which, from genetic evidence, seemed probably to be composites, in part haploid and in part diploid. In one case the haploid region includes the location of a sec-

ondary sex-organ, the sex-comb (present in the normal male, absent in the female). In the mosaic the sex-comb is absent in the region that is haploid. In other words the haploid group of chromosomes consisting of three autosomes and one X gives, as anticipated, the same kind of result as six autosomes and two X's. The balance is the same in each although the haploid region of the mosaic has only one X, as has the normal male; but in the male this is offset by six autosomes.

The converse case is reported by Wettstein who produced by artificial means gametophyte moss plants that were diploid. If these arise from a haploid female gametophyte cell they are female, and if from a haploid male gametophyte cell they are male. In both cases the balance remains as before. It is apparent that sex-determination is not in these cases regulated by the number of chromosomes but by the relation of contrasted sets of genes or chromosomes to one another.

Sex and its Definition in Lower Plants.

The question of sex terminology appears in its most acute form in the results of recent work on certain groups of gilled fungi or toadstools, Basidiomycetes. In this group, according to the recent statement by Hanna "The problem of sex has occupied the attention of mycologists for more than a hundred years." The discoveries of Miss M. Bensaude (1918), of Kniep (1919-23), of Miss Mounce (1921-22), Buller (1924) and Hanna (1925) have brought to light an extraordinarily interesting situation. In order to simplify the description of this work, the recent paper of Hanna is here followed closely. By means of a new and refined technique, single spores from the gills of the toadstool can be isolated. From each spore a single mycelium of hyphae can be grown in dung-agar cultures. Each such monosporous mycelium can then be tested by bringing it

in contact with the others one by one. Certain of these combinations will unite and form a secondary mycelium on which "clamp connections" develop, indicating that the mycelia are of "opposite sexes." Later, fruiting bodies or toadstools develop from such mycelia. On the other hand, other combinations, when made, do not form secondary mycelia with clamp connections, and, as a rule, do not produce fruit bodies. The union is interpreted to mean that the mycelia in question are of the same sex.

		AB			ab				Ab		aB
		51	52	54	55	57	58	59	50	56	53
AB	51	−	−	−	+	+	+	+	−	−	−
	52	−	−	−	+	+	+	+	−	−	−
	54	−	−	−	+	+	+	+	−	−	−
ab	55	+	+	+	−	−	−	−	−	−	−
	57	+	+	+	−	−	−	−	−	−	−
	58	+	+	+	−	−	−	−	−	−	−
	59	+	+	+	−	−	−	−	−	−	−
Ab	50	−	−	−	−	−	−	−	−	−	+
	56	−	−	−	−	−	−	−	−	−	+
aB	53	−	−	−	−	−	−	−	+	+	−

TABLE 1.

Now, when monosporous mycelia from the same strain (*i.e.*, from plants living in the same locality) are tested, the results are like those in Table 1. Here, the presence of clamp connections, formed after the union of two monosporous mycelia, is indicated by the + sign. Failure in this respect is indicated by the — sign. In the Table the mycelia fall into four groups (those belonging to the same group have been brought together in the Table). The result is interpreted as meaning that the spores of a single fruit body of the species studied, namely, Coprinus lagopus, belong to four sexual groups.

These four groups as Kniep first showed, can be accounted for on the assumption of two pairs of Mendelian factors that may be designated as Aa and Bb. If these factors are segregated, at the time when the spores are formed on each basidium, there will be present on each toadstool four kinds of spores, AB, ab, Ab, aB, each of which gives rise to a mycelium of the same genetic composition. As shown in Table 1, only those mycelia differing in both factors unite and form clamp connections. This means that there are four sexes, and only those with different sex factors can combine.

There is also a cytological background that accords excellently with these genetic assumptions. The nuclei in the monosporous mycelia lie singly in the protoplasm. After the union of two mycelia, the nuclei in the derived (secondary) mycelium are in pairs. It is reasonable to assume that one member of each pair has come from one mycelium, the other one from the other mycelium. At the time when the four spores are about to develop, reduction is supposed to take place, so that each spore comes to contain a reduced nucleus. Each spore gives rise to a new reduced mycelium. Such a picture accords with the reduction process in higher plants and animals and serves to bring these moulds into line with the genetic results that take place when the chromosomes are reduced from diploid to haploid gametes. It is true that, as yet, it has not been shown in *Coprinus* and related species that we are dealing with a diploid-haploid relation, but it seems not improbable that this is a correct interpretation of the facts as far as known. If so, the sorting out of the genetic factors in these toadstools is the same in principle as that shown by other plants and animals.

The preceding relations hold for strains occurring in any one locality. If strains from different localities are tested, an extraordinary result is found. All the monos-

porous mycelia of one strain unite (*i.e.*, give mycelia with clamp connections, etc.) with all the monosporous mycelia of the other strains. In Table 2 the pairing of eleven

		A^4B^4			a^4b^4	A^4b^4				a^4B^4		
		4	7	8	5	2	6	10	11	1	3	9
A^2B^2	25	+	+	+	+	+	+	+	+	+	+	+
	26	+	+	+	+	+	+	+	+	+	+	+
	27	+	+	+	+	+	+	+	+	+	+	+
	28	+	+	+	+	+	+	+	+	+	+	+
a^2b^2	20	+	+	+	+	+	+	+	+	+	+	+
	23	+	+	+	+	+	+	+	+	+	+	+
	24	+	+	+	+	+	+	+	+	+	+	+
a^2B^2	21	+	+	+	+	+	+	+	+	+	+	+
	29	+	+	+	+	+	+	+	+	+	+	+
	30	+	+	+	+	+	+	+	+	+	+	+
A^2b^2	16	+	+	+	+	+	+	+	+	+	+	+

TABLE 2.

monosporous mycelia from a fruit body from one locality (Edmonton, Canada) are shown to have united with eleven monosporous mycelia from another locality (Winnipeg). The same results were obtained whenever strains from different localities were paired. The combinations carried out by Hanna gave twenty sexes for *Coprinus* and no doubt the number could be greatly increased by extending the combinations to other localities.

Not only was this cross-hybridizing carried out, but the factorial hypothesis was further tested by experiments on the crossed strains themselves. If the factors from the different strains are treated as allelomorphic pairs, and the factors in one strain are designated by Aa and Bb, and those in another strain by A^2a^2 and B^2b^2, there will be sixteen possible hybrids formed by the union of the

mycelia from these two varieties, and each mycelium of such hybrid origin will behave in a manner similar to that shown by mycelia from a single source, in that two given mycelia form clamp connections only in case they carry no factors in common.

Here we have the phenomenon of sex exhibited on a grand scale if we interpret the factors involved as sex factors in the conventional sense. There is no objection to using the word in this way if it seems advantageous to define sex on such a basis. Personally, I think it is simpler to interpret the results in the same way that East has interpreted the results of his tobacco investigations, and call the factors involved self-sterility factors (see below). The explanation is the same in principle, whatever language one prefers to use in describing them.

Under the title of Research on Relative Sexuality, Hartmann has recently described results that he obtained with the marine alga, *Ectocarpus siliculosus.* The motile swarm-spores set free from the plants are externally alike, but according to their subsequent behavior they fall into two classes "females" and "males." The former

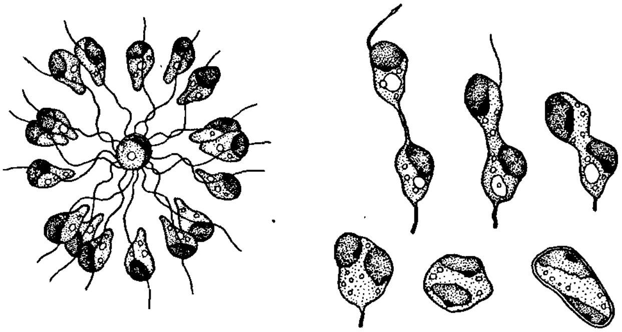


FIG. 137a.

Swarming of male gametes around a "female" gamete (to left). Union of "male" gamete and a female gamete (to right). (After Hartmann.)

quickly settle down, while the latter continue to swarm for some time and surround the female individual (Fig. 137a). One of the male swarm-spores fuses with the resting female swarm-spore. Hartmann isolated individual parent plants and when the swarm-spores were set free, tested these *en masse* against each other. A typical result is given in Table 3 (to the left) where union is indicated by

	3♂	4♀	5♀	7♀	11♂	13♀	14♀
3♂	−	+	+	+	−	+	+
4♀	+	−	−	−	+	+	−
5♀	+	−	−	−	+	−	−
7♀	+	−	−	−	−	+	−
11♂	−	+	+	−	−	+	−
13♀	+	+	−	+	+	−	+
14♀	+	−	−	−	−	+	−

	31♀	32♀	33♂	35♂	38♂	40♂
31♀	−	−	+	+	+	+
32♀	−	−	+	+	+	+
33♂	+	+	−	+	−	−
35♂	+	+	+	−	+	−
38♂	+	+	−	+	−	−
40♂	+	+	−	−	−	−

TABLE 3.

the + sign and failure to unite by the — sign. Each kind is tested against each of the other kinds. In most cases the swarm-spores from a given individual behave constantly either as males or as females with the other types, but in a few instances swarm-spores that acted as females in some combinations acted as males in other combinations. Thus No. 4 (see Table 3, to left) and No. 13 give results inconsistent with their reaction in other combinations. Another exception is found in the reactions between No. 35 and No. 38 (see Table 3, to right), both of which are designated as males from their other behavior, yet react to each other as male and female. Hartmann speaks of certain individuals as strong females and others as weak females according to the number of "clusters" that they give in different combinations, and concludes that weak females may function as males when opposed to

strong females, and that weak females may function as females when opposed to strong males. To what extent these relations may be affected by age-factors (settling down, for example), or by environmental factors is not entirely clear, although Hartmann's statement that the relations hold from day to day as the swarm-spores are tested seems to exclude such explanations. Unfortunately the material is not suited to a genetic analysis of the factors involved. Whether the quicker settling down of the gametes from a certain individual is a sufficient index of their "sex" and if so, how this is changed when a weak female acts as a male, etc., is not apparent. Nevertheless the failure of gametes from the same plant to copulate appears to put the phenomenon in the same category as self-sterility and its correlative cross-fertility. To designate this as a criterion of sex is perhaps largely a matter of choice or of definition at present. Personally, it seems to me to confuse rather than to clear up the problems involved to use the word sex in this connection where the phenomenon is one of union or non-union of gametes rather than one of sex as commonly understood.

The question then may be asked whether it may not be simpler and less likely to lead to confusion to call the factors, involved in the union of the mycelia of *Coprinus* and of the swarm-spores of *Ectocarpus*, self-sterility factors rather than sex-factors. The recent important results of East in his studies on self-sterility in tobacco have for the first time put the oft-studied problem of cross- and self-fertility in flowering plants on a well-tested genetic basis. These phenomena in the flowering plants have many resemblances to the union of the gametes in *Coprinus* and *Ectocarpus* and while the *modus operandi* of the process may not be identical in all cases, there is much to suggest that the genetic and physiological backgrounds may be essentially alike.

In a brief paper East and Mangelsdorf have given a summary of work extending over several years dealing with the inheritance of self-sterility in crosses between two species of tobacco, viz. *Nicotiana alata* and *N. forgetiana*. Only the most general conclusions can be given here. By special manipulation several selfed, homozygous strains of self-sterile individuals were carried through twelve generations to obtain suitable material for testing the problem. As an example the results of one type of the families produced may be given. Three kinds of individuals a, b and c were found. Each individual of any one of these kinds is sterile with any other individual of its kind and fertile with each individual of the other two kinds; but the progeny resulting from reciprocal crosses is different. Thus, a ♀ by c ♂ gives b and c individuals only, while c ♀ by a ♂ gives only a and b individuals. Two classes always appear in equal numbers, but the class of the mother is never represented in the offspring. The explanation is as follows. If three allelomorphic genes are present in such a family $S_1S_2S_3$ and if class a $= S_1S_3$; class b $= S_1S_2$; class c $= S_2S_3$ and if the pistil of a plant affords the stimulus for the growth of the pollen which bears sterility factors other than its own, the results find a consistent explanation. For instance, plant c (S_2S_3) affords a sufficient stimulus only to pollen carrying factors other than S_2S_3. Only pollen bearing the factor S_1 can penetrate the style and fertilize the eggs. The progeny will be S_1S_2 (class b) and S_1S_3 (class a) in equal numbers. Reciprocally, a ♀ (S_1S_3) by c ♂ (S_2S_3) permits the S_2 pollen alone to penetrate the eggs giving S_1S_2 (b) and S_2S_3 (c). This result which is typical of all the others, explains why the female combination is absent in the progeny, why the progeny of reciprocal crosses is different and why the progeny-counts of two classes other than female are equal regardless of which of the other two classes serves as the male parent.

There are several ways of testing the validity of this hypothesis. The tests have been made and the hypothesis confirmed. This convincing analysis, the result of carefully planned genetic experiments, is a contribution of the first rank to a problem that has baffled students of fertilization for seventy-five years and more. The solution is not only a keen genetic analysis of the case but gives an insight into the physiological reactions between the haploid pollen tube and the diploid tissue of the female. It has been shown by direct observation that the rate of growth of the pollen tube in the tissue of the female is consistent with the view that a differential rate of growth is actually present. The nature of the relation is not known at present but may reasonably be assumed to be chemical. It is possible that the same or a similar chemical reaction with its genetic basis may account for the self-sterility observed in the union of the genetically unlike mycelia of the lower forms. If this can be established the genetic problem has to do primarily with self-sterility factors that are probably Mendelian genes. It may seem of doubtful value to identify these factors with sex factors which conventionally at least apply to somatic differences in dioecious types or to those with separate sexes. It is true that amongst these differences are those concerned with producing eggs and sperm whose main function is to unite with each other, but, as generally understood, these functions are less conspicuous than those appertaining to the bodily constitution of male and female individuals.

CHAPTER XVI

INTERSEXES

IN recent years some curious individuals have been found in species with separate sexes, that combine to varying degrees the characters of males and females. At present most of these intersexes, or sex intergrades, may be referred to four sources: (a) to changes in the ratio of the sex-chromosomes to the rest of the chromosomes; (b) to changes in the genes not visibly connected with changes in chromosome number; (c) to changes that result from crossing wild races, and (d) to changes in the environment.

Intersexes from Triploid Drosophila.

To the first class of intersexes belong some of the offspring of triploid females of Drosophila. When the eggs of a triploid female mature, the chromosomes are irregularly distributed, and, after the polar bodies have been given off, the eggs are left with different numbers of chromosomes. If such a female is mated to a normal male whose sperm carries one set of chromosomes, the offspring that come through are of several kinds (Fig. 138). There is reason to believe that many eggs do not develop at all, because they lack the right combination to produce a new individual; but amongst the survivors there are some triploids, more diploids (normals), and a few intersexes. These intersexes (Fig. 139) have three sets of autosomes and two X-chromosomes (Fig. 138). The formula is 3a+2X (or 3a+2X+Y). Thus, although the intersex has the same number of X-chromosomes as has

an ordinary female, it has one set more of the ordinary chromosomes. It is clear from this that sex is determined not by the actual number of the X-chromosomes present, but by the ratio of these to the other chromosomes.

Diploid	Triploid	Tetraploid
2a+2X=♀	3a+3X=♀	4a+4X=♀
2a+X+Y=♂	3a+X+Y=Super ♂	4a+2X+Y=♂
	3a+2X=Intersex	
	3a+2X+Y= "	

FIG. 138.

Diagram giving the formulae of normal, triploid, tetraploid, and intersexes of Drosophila melanogaster. The tetraploid male (4a+2X+2Y) is hypothetical. Besides these classes the triploid female gives rise to superfemales (2a+3X). (After Bridges.)

From these exceptional relations amongst the chromosomes, described by Bridges, he concluded that sex is determined by a balance between the X's and the other chromosomes. We may think of the X-chromosomes as containing more of the genes that go to produce a female, and the rest of the chromosomes as containing more of the genes that go to produce a male. In the normal female, 2a+2X, the two X's turn the scale toward femaleness. In the normal male there is only one X, and the balance turns the other way. The triploid, 3a+3X, and the tetraploid, 4a+4X, have the same balance as the normal female and are practically identical with her. The expectation for the tetraploid male, 4a+2X+Y (that has not yet been obtained), is that he will be like the normal male, since the balance is the same in both.

This evidence from triploids gives no specific information as to the occurrence of genes for sex-determination. If we think of the chromosomes only in terms of genes, it *follows that genes are involved, but the evidence does not* show what they are like. Even if genes are involved, we

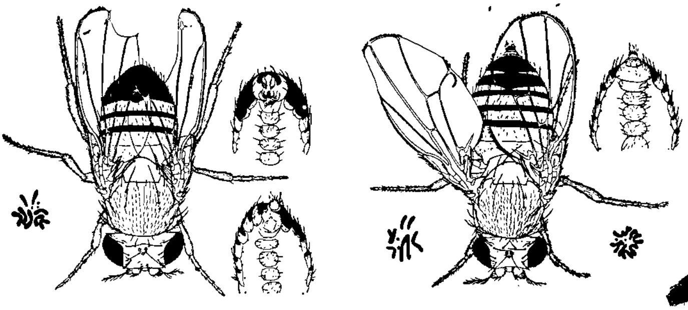


FIG. 139.

To the left the female type of intersex of Drosophila, as seen from above and below. The chromosome groups show two X's, three each of the larger autosomes (II and III) and usually (two here) small IV-chromosomes. To the right the male type of intersex, as seen from above and below. The chromosome group has two X's, three each of II and III, and usually only two IV's (here three).

cannot state whether there is one gene in the X that stands for femaleness, or hundreds of such genes. Similarly for the ordinary chromosomes—the evidence does not tell us whether the genes for maleness, if there be such, are in all the chromosomes or in only one pair.

There are, however, two ways in which we may hope, some day, to discover something about the genes that influence sex. The X-chromosome may become fragmented in such a way as to reveal the location of the special genes relating to sex, if there are such. The other hope rests on the occurrence of a gene mutation. If other

genes mutate why not sex-genes, if there are such specific genes?

There is, in fact, one certain case of the occurrence of an intersex that arose by a mutant change in the second chromosome of Drosophila. Sturtevant (1920) studied this case, and found it due to a change in genes in the second chromosome. The female is turned into an intersex. Unfortunately, the evidence does not show whether or not a single gene only was affected.

It is apparent, from what has been said, that while we can interpret the sex-determining formulae in terms of genes, we have no direct evidence, at present, that there are any specific genes for maleness and femaleness. There may be such genes, or it may be that sex is determined by a quantitative balance between all the genes. But since we have much evidence that the genes differ amongst themselves very greatly as to the kind of effects that they produce, it seems probable, I think, that certain genes may be more influential as sex differentials than are other genes.

Intersexes in the Gypsy Moth.

Goldschmidt has carried out an extensive series of very interesting and important experiments in the production of intersexes in racial crosses of the gypsy moth.

When the female of the common European gypsy moth (Fig. 140a, b) is crossed to a Japanese male, equal numbers of male and female offspring are produced. When the cross is made the other way the sons are normal, but the daughters are intersexes or male-like females (Fig. 140c, d).

Later Goldschmidt carried out an elaborate series of crosses between the European species and several Japanese species and also between different races of Japanese varieties or species. The results may be arranged in two

series. In one series the females are finally all changed over into males; in the other series the males are changed over into females. The former change is spoken of as female intersexuality; the latter, as male intersexuality. Without attempting to review the long series of experiments from which the evidence has come, Goldschmidt's theoretical deductions may be stated as briefly as possible.

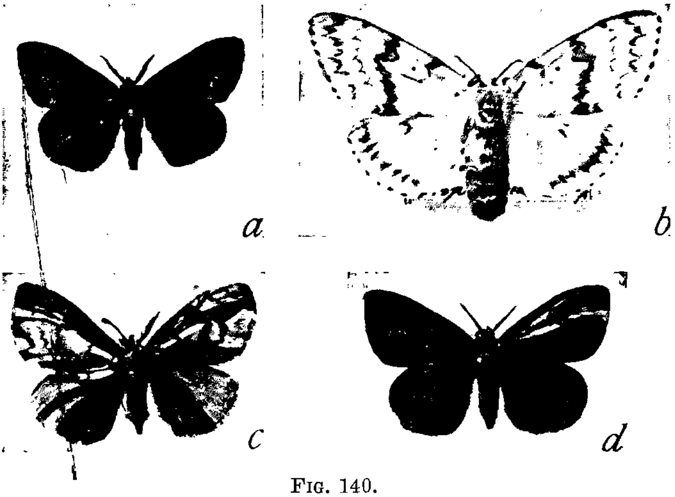


FIG. 140.

a, Male and *b*, female of Lymantria dispar; *c* and *d* two intersexes. (After Goldschmidt.)

The formula he uses for the male is MM and for the female Mm; in other words, the WZ-ZZ formula. In addition, however, Goldschmidt adds another set of sex-determining factors that at first he called FF, which stand, in a way, for femaleness. The male factors are supposed to segregate, as do Mendelian factors in general, but the FF factors do not segregate and are transmitted only through the egg. They were supposed to reside in the cytoplasm, although Goldschmidt has later shown an inclination to locate them in the W-chromosome.

By assigning numerical values to the big M's (none to the m) and to FF he has built up a scheme to show how, in the cross first mentioned, equal numbers of males and females result when the cross is made in one direction, and intersexes when it is made in the opposite direction.

In like manner, by assigning suitable values to the letters in each of the other crosses an approximately consistent account can be given of the results.

The unique feature of these formulas of Goldschmidt is not, in my opinion, the numerical values attached to the factors, for these are arbitrary, but the statements that the results can be explained only by the assumption that the factors for femaleness are in the cytoplasm, or else in the W-chromosome. In this respect his view is different from the condition that Bridges has found in Drosophila from a study of triploids, where the opposing influences are in the X-chromosomes and in the autosomes.

Goldschmidt has recently (1923) reported a few exceptional cases in which the evidence indicates, he believes, that the female-producing factors lie in the W-chromosome. One such case relates to certain racial crosses, where, through non-disjunction, a female receives a W-chromosome (Y in his formula) from the father and the Z from the mother. This is the reverse of the ordinary transmission of these chromosomes. The results indicate that the female factors follow the W. Logically, the evidence appears satisfactory, but on the other hand both Doncaster and Seiler have reported a few exceptional female moths in which the W-chromosome is at times absent. These moths were normal females in every respect and bred as such.[1] They could not be

[1] There are 56 chromosomes present in the female and in the male of Abraxas. That one of those in the female is a W-chromosome is very probable, from Doncaster's discovery of a strain in which the females have only

females, on Goldschmidt's view, if the female factors are in the W-chromosome.

Before leaving Goldschmidt's theories a very interesting suggestion that he has made to account for the mosaic character of the intersexes must be mentioned. The intersex consists of parts that are male and parts that are female—patches of each. Now Goldschmidt suggests that this is brought about by a difference of time at which the male and the female parts are determined in the embryo. Expressed in a different way, one may say that in certain combinations of the sex factors of the racial hybrid-intersexes, the individual starts as a male. The organs of the embryo that are the first to be laid down are therefore male-like. In later stages, the female factors overtake and surpass the male-producing ones, so that the later stages of the embryo are like the female. Hence the mosaic characters for this class of intersexes.

Conversely, in the reciprocal type the embryo starts under the influence of the female factors, and the first parts of the embryo to be laid down are female-like. In later stages the male-producing factors overtake and surpass the female tendencies, and male organs develop.

In general Goldschmidt treats the genes as enzymes, although at times he concedes that the enzymes in question may be the product of the genes, which seems more consistent with what we infer as to the nature of genes. Until we can discover whether all the genes are active all the time, or whether all or some of them are active only when the embryo is passing through certain stages of development, we can do little more than speculate as to what takes place.

55 chromosomes. The absence of one chromosome, presumably the W, produces no visible changes in the character of the female. That the missing chromosome is really a sex-chromosome and not an autosome is highly probable from the fact that individuals lacking it are always females.

The Free Martin.

It has long been known that when twins in cattle are born, one of which is a normal male, the other a "female," the latter is usually sterile. It is known as a free martin. The external genitalia of the free martin are generally female, or much more female-like than male, but it has been demonstrated that the gonads may resem-

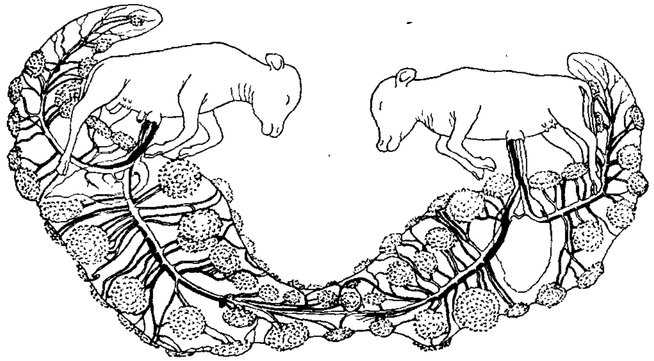


FIG. 141.

Two embryo calves, one of which will become a free martin, whose placentas are united. (After Lillie.)

ble testes. It was shown by Tandler and Keller (1911) that the twins (one of which is a free martin) come from two eggs, and Lillie (1917) has fully confirmed this fact. It was also shown by Tandler and Keller that there is present a vascular connection between the two embryos in utero by means of intra-chorionic connections (Fig. 141). Magnussen (1918) described a considerable number of free martins of various ages, and has shown by histological examination that well-developed testicular-like organs are present in older free martins, *i.e.*, that the characteristic tubular structure of the testes, including rete tubules, sexual cords, and epididymis, is present.

Chapin (1917) and Willier (1921) have confirmed these observations, and the latter especially has given a detailed account of the transformation of the "indifferent stage" of the ovary into a testis-like structure.

Magnussen (who erroneously believed the free martin to be a male) found no spermatozoa in the "testes." Their absence he believed to be due to the retention of the testes within the body cavity (cryptorchidism). It is known that in those mammals in which the testes normally descend into the scrotal sacs, sperm-cells are absent when the testes are retained, but in the early embryo germ-cells appear while the testes are still within the body cavity. In the free martin there are, according to Willier, no primordial germ-cells present in the so-called testis.

Lillie's conclusion that the free martin is a female whose gonads have been transformed into a testis-like organ is so strongly supported by this evidence that it can scarcely be questioned, but whether the effect is to be referred to the composition of the blood of the male, or, as he thinks, to a testicular hormone in the blood is open to question, since there is at present no evidence of any specific substance produced by the gonad of the male embryo that produces such an effect on the development of the young ovary. Since all the tissues of the male embryo have the male chromosomal composition, the blood may likewise have a different chemical constitution from that of the female, and affect, in consequence, the development of the gonad. It is generally recognized that the young gonads have rudiments of both ovary and testes present; or, as Willier puts it, "the primordium of each male structu 'veloped in the free martin gonad is present in the 'ary at the time of sex differentiation." The most significant fact in these observations is the absence of male germ-cells in the free martin. The influ-

ence of the blood of the male co-twin does not bring about the transformation of the primordial egg cells into sperm-producing cells.

Individuals with both male and female sexual organs, even including ovaries and testes, have been frequently recorded in mammals, including man. These were formerly called hermaphrodites, but now are sometimes called intersexes or sex intergrades. The conditions that give rise to them are unknown. Crew reports twenty-five cases in goats, seven in pigs.[2] These, Crew believes, are modified males, since testes were present in all of them. Baker has recently reported that the sex intergrading pigs are surprisingly common on some of the islands [New Hebrides]; "one finds them in nearly every little village." This tendency to sexual abnormality is inherited through the male in some cases reported by him. Baker regards them as probably transformed females.[3]

[2] Pick and others had earlier described such individuals, two in horses, one in sheep, one in cattle.

[3] Prange has described four hermaphroditic goats with external female genitalia, but with undeveloped mammae. In sex behavior and in coat they were male-like. Internally both male and female ducts were present, but the gonads were testes (cryptorchid).

Miss Harman has described a "gynandromorphous" cat that had a testis on the left side and an ovotestis on the right side. The reproductive system of the left side is like that of a normal male, while that of the right side is like that of the female, except for the size, etc., of the uterine tube.

CHAPTER XVII

SEX REVERSALS

IN the older literature dealing with sex-determination the idea is often expressed that the sex of the embryo is determined by the environmental condition under which the embryo develops. In other words, the young embryo has no sex, or is indifferent, and its fate is determined by its environment. It is unnecessary to go over again the evidence from which this idea originated, since practically all of it has been shown to be defective in one way or another.

In recent years there has been some discussion concerning the reversal of sex, which means, by implication, that a male, already determined as such, can become changed into a female, and vice versa. It has even been suggested that, if this can be shown to occur, the genetic interpretation of sex is discredited or even overthrown. It is scarcely necessary to point out that there is nothing in the theory of sex as determined by sex-chromosomes or genes contradictory to the idea that other influences may so affect the development of the individual as to change or even reverse the balance normally determined by the genes. To fail to appreciate this is to fail entirely in grasping the ideas that underlie the theory of the gene; for this theory postulates no more than that in a given environment such and such effects are expected as a result of the genes present.

It is no more surprising that a genetic male might, in an abnormal environment, turn into a female, or vice versa, than that an individual might at one stage of its

development function as a male and at a later stage as a female. It remains, then, entirely a question of fact whether evidence can be produced proving that an individual having the genetic make-up of a male may, under a

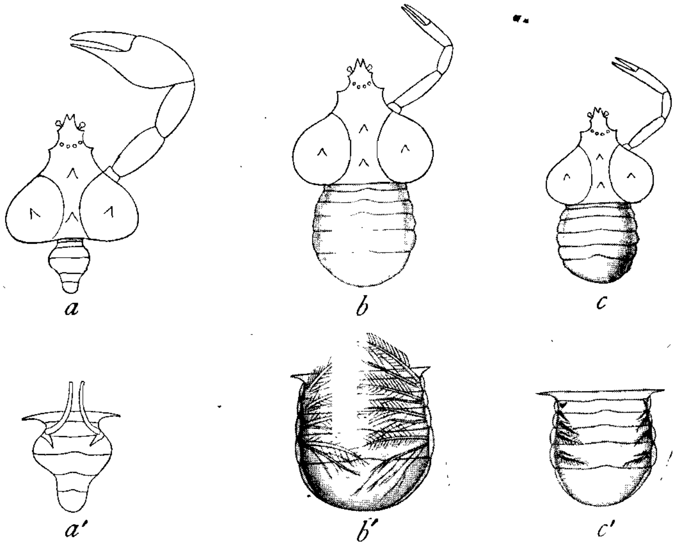


Fig. 142.

Spider crab, *a*, normal male; *a′*, abdomen of normal male from below; *b*, normal female; *b′*, abdomen of normal female from below; *c*, parasitized male; *c′*, abdomen of parasitized male from below. (After Geoffrey Smith.)

different set of conditions, become a functional female, or the reverse. Several such cases have been reported in recent years which call for a careful and unprejudiced scrutiny.

Environmental Changes.

It was shown by Giard in 1886 that when the males of crabs are parasitized by other crustaceans, such as Pelto-

gaster or Sacculina, they then develop external characters like those of a female. In Fig. 142a, an adult male crab is shown, with its large claws, and in a′ the under side of its abdomen with the copulatory appendages, and in b an adult female is shown, with her small claws, and in b′ the under side of her abdomen with the setose bifurcated egg-carrying appendages. In c is shown a male that has been infected at an early stage; the claws are small, resembling those of the female, and the abdomen is broad and female-like; in c′ the under side of the abdomen of the infected male is shown. It has small bifurcated appendages like those of the female.

The parasite sends long root-like processes into the body of the crab, on which the parasite lives by absorbing the juices, and may, in turn, set up physiological processes in the crab itself. The testes of the crab may not at first be affected, but later may degenerate. In one case, at least, where the parasite had fallen off, Geoffrey Smith found large germ-cells developing in the regenerating testis, which he interpreted as eggs.

Giard left open the possibility as to whether the change in the crab was due to the absorption of the testis, or whether the action was more direct on the host. Geoffrey Smith has brought forward some evidence relating to fat in the blood, and certain arguments in favor of the view that the change in the crab is due to the physiological effects on the host. There is no evidence in crustacea that the destruction of the gonads affects the secondary sexual characters.

In insects, where there is evidence from castration, it has been shown that the removal of the testes or ovary does not alter the secondary sexual characters. It is all the more significant, therefore, that in one case described by Kornhauser (1919), in a bug (Thelia) that is parasitized by a hymenopter (Aphelopus), the male shows

the secondary characters of the female or at least fails to develop those of the male.

While most of the decapod crustacea have male and female sexes there are a few cases where both ovaries and testes are present in one or in both sexes, and there are a few cases where the young males may have large egg-like cells in the testes. Several crayfish have also been described that are sex intergrades, but no complete reversals are known.[1]

In Daphnians, and related forms, intersexual individuals have been described by several observers (Kuttner, Agar, Banta, etc.), but no complete reversals are known. Sexton and Huxley have recently described some individuals of Gammarus that are called female intersexes, which, "on reaching maturity, more or less closely resemble females but gradually come to resemble males more and more nearly."

Most of the barnacles are hermaphroditic. In some genera there are, in addition to the large sessile hermaphrodites, minute complemental males, and there are a few other species with sessile female individuals and complemental males. The sessile individuals are generally supposed to be true females, but Geoffrey Smith has suggested that if a free-swimming larva becomes fixed it grows to full size, passing through the male stage to become a female, but if a free-swimming larva attaches itself to a female it develops no further than the male stage. This seems to mean no more than that the environment determines whether a potential individual develops into a female or being arrested in its development becomes a male.

The last case is similar to another in the gephyrean worm, Bonellia, described by Baltzer. If a free-swimming

[1] See Faxon, Hay, Ortman, Andrews, Turner.

larva attaches itself to the proboscis of a female it remains extremely small and develops testes, but if it settles down by itself it becomes a large female individual. The evidence does not positively rule out the possibility that there are two kinds of individuals that behave in one or the other way, but Baltzer's interpretation seems very probable.

If the correct interpretation for the barnacles and for Bonellia is that suggested above, it means that sex is determined in these forms by environmental conditions, which means, in terms of genes, that all the individuals are alike.[2]

Changes of Sex Associated with Age.

Biologists are familiar with several cases both in animals and in plants where an individual may first function as a male and later as a female, or vice versa. But the special cases in which sex reversal takes place are those whose sex is known to be *determined* in the first place by their chromosomal make-up, yet which are said, in rare cases, to turn into the opposite sex without changing their chromosome complex.

The hagfish, Myxine, according to Nansen and Cunningham, is male when young, and later becomes female; but the subsequent observations of the Schreiners indicate that while the young Myxine is hermaphroditic—the anterior end of the gonad being a testis, the posterior an ovary—it is not so functionally. Later each individual becomes definitively male or female.

Breeders of the aquarium fish, Xiphophorus helleri, have reported at various times that females change into males, but, unfortunately, as yet there is no account of

[2] According to Gould, if a young individual of Crepidula plana settles down near a female it becomes at first a male and remains so permanently; but if it settles down away from large individuals it fails to develop testes and passes later into a female.

the frog, the gonads often appear to be intermediate. The classification of individuals of this sort as male or female has led to much dispute. In recent years it has been shown that these intermediate forms often become males, and it has even been claimed that in many races all males pass through this stage.

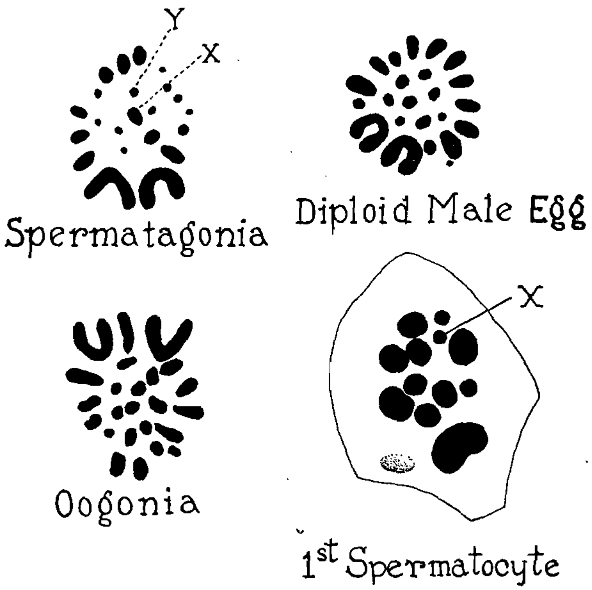


FIG. 144.

Chromosome groups, spermatogonia and oögonia, and diploid male egg of Perla. (After Junker.)

The experiments of Richard Hertwig have shown that by delaying the fertilization of the frog's egg, the proportion of males is greatly increased, and, in extreme cases, all individuals become males. The attempts to correlate these cases of retarded fertilization with chromosomal alterations have not been successful.

Further study has shown that the earlier results were obscured by failure to realize that different races of frogs show remarkable differences in the development of the testes and ovaries. Witschi has shown that in general there are two kinds or races of the European grass frog, Rana temporaria. In one of these the testes and ovaries differentiate directly from the early gonad. Such races are found in the mountains and in the far North. In the other races, living in the valleys and in the middle of Europe, the gonad in those individuals that will become males passes through an intermediate stage in which large cells are present in its interior which he regards as immature eggs. These are replaced later by a new set of germ-cells that become the definitive sperm. These races are called undifferentiated races.

Swingle also finds in the American bullfrog two types or races, speaking broadly, in one of which the testes and the ovaries differentiate early from the progonad. In the other races the differentiation is delayed. In the female of these races the larger cells of the progonad become later the definitive eggs, but in the male the progonad persists for some time after the female has differentiated. Its large cells may differentiate into spermatozoa. These are, however, later absorbed for the most part, but some of those that remain undifferentiated become the definitive sperm-cells. Swingle does not interpret the large cells in the male progonad as eggs, but as male spermatocytes. He shows that these cells pass through an abortive maturation division and then, for the most part, break down. In other words, the male does not pass through a female stage, but makes, as it were, an abortive attempt to form sperm before its second and later differentiation takes place.

Whatever interpretation is placed on these large cells in the progonad, the important point for present con-

sideration is whether external or internal conditions may affect the progonad of the prospective female in such a way that it produces later functional sperm-cells. Witschi's evidence is in favor of such a transformation in those races that are indifferent.

In the following table (Table III) Witschi has brought together the sex ratios reported by different observers from different parts of Germany and Switzerland. In the right-hand column the per cent of females is given; 50 per cent means a 1 to 1 ratio. It will be seen that in the first two groups (Group I and II) the sex ratio is approximately 1 to 1, while in the last three groups (III, IV, V) the proportion of females is higher, culminating in those regions where all the individuals from a pair may be females (100 per cent). These belong to the indifferent races.

The most important facts discovered by Witschi relate to the inheritance of these differences shown by the differentiated and undifferentiated races. Hertwig made crosses between females and males of the different races.

(1) ♀ undif. by ♂ differ.=69 undif. ♀ + 54 ♂
(2) ♀ dif. by ♂ undif.=34 ♀ + 52 ♂

In (1) the daughters were all undifferentiated; in (2) the daughters differentiated early. Witschi draws the conclusion that eggs of a differentiated race are more strongly female-determining than the eggs of an undifferentiated race.

In another experiment Hertwig crossed undifferentiated races whose "female determining power" (Kraft) was greater or less. Witschi concluded that weak eggs by strong sperm give the same result as strong eggs by weak sperm. "Eggs and female determining sperm of the same type have the same genetic constitution."

TABLE III

SEX RATIOS IN DIFFERENT LOCAL RACES OF THE GRASS FROG SHORTLY AFTER METAMORPHOSIS (AT MOST TWO MONTHS)

Those with asterisk were caught in the open.

Group	*Locality*	*Author*	*Number of Animals Examined*	*Per cent of Females*
I	Ursprungtal (Bayr. Alpen)	Witschi (1914 b)	490	50
	Sertigtal, Davos (Rätische Alpen)	Witschi (1923 b)	814	50
	Spitalboden (Grimsel, Berneralpen)	Witschi	46*	52
	Riga	Witschi	272	44.5
	Königsberg	Pflüger (1882)	370	51.5
			500*	53
II	Elsass (Mm)	Witschi	424	51
	Berlin	Witschi	471	52
	Bonn	Witschi	290	43
	Bonn	v. Griesheim und Pflüger (1881-82)	806	64
			668*	64
	Wesel	v. Griesheim (1881)	245*	62.5
	Rostock	Witschi	405	59
III	Glarus	Pflüger (1882)	58	78
IV	Lochhausen (München)	Witschi (1914 b)	221	83
	Dorfen (München)	Schmitt (1908)	925*	85
	Utrecht	Pflüger (1882)	780	87
			459*	87
V	Freiburg (in Baden)	Witschi (1923 a)	276	83
	Breslau	Born (1881)	1,272	95
	Breslau	Witschi	213	99
	Elsass (r)	Witschi	237	100
	Irschenhausen (Isartal südl. München)	Witschi (1914)	241	100
		Total	10,483	

The chromosome composition of frogs has been in dispute for several years, not only as to the number of chromosomes present, but as to whether the male or the female is digametic. The most probable number of chromosomes for several species seems to be 26 (n=13). Other num-

experiments were not made with the same male for the same sets of eggs, the results are doubtful. Hertwig himself points out there are many resemblances between the effect of cold and that of overripening. Many embryos are deformed. Witschi has confirmed Hertwig's results (with the Irschenhausen race). Eggs estimated to be 80 to 100 hours overripe gave 74 ♂, 21 ♀, 20 indifferent tadpoles.[3]

Richard Hertwig compared the sex ratio of normal and delayed eggs (67 hours' interval) with the following results. Larvae 49 days old (just before metamorphosis) that came from normal fertilization gave 46 indifferent ♀; those from delayed fertilization, 38 indifferent ♀ and 39 ♂. The normal frogs about 150 days old were differentiated females, indifferent females as to gonads, and males (numbers not given), and from the delayed eggs 45 indifferent ♀ and 313 ♂. Yearling frogs gave 6 ♀ and 1 ♂ (normal fertilization) and 1 ♀ and 7 ♂ (delayed fertilization). The overripeness here would seem to hasten the male differentiation and in the second place transform the indifferent individuals (here ranked undifferentiated females) into males.

The interpretation of the results produced by overripening the eggs is still very obscure. Taken at their face value they seem to show that individuals that would normally become females may become males. As yet no genetic tests have been made of the sex-determining properties of the spermatozoa of individuals obtained in this way. Theoretically, these should be homogametic. It seems improbable that such individuals could live and function under natural conditions, for, although overripeness must not infrequently occur, normal males giving 100 per cent females are practically unknown. Wit-

[3] There was 20 per cent mortality in the tadpoles and 35 per cent in the young frogs.

schi has pointed out that the overripe eggs undergo an unusual type of cleavage, and that a few embryos that he examined show internal defects, but the relation of these defects to the transformation of females into males is not apparent.

The possibility of transforming individuals having an undifferentiated or juvenile hermaphroditic gonad (or progonad) into females by external agencies is furnished by the following evidence from Witschi's experiments (1914-1915).

Tadpoles of the Ursprungtal race, that is, probably a differentiated race, gave, at 10° C., 23 males and 44 females; at 15° C., 131 ♂ and 140 ♀; and at 21° C., 115 ♂ and 104 ♀. The sex of the tadpoles of this race is apparently not affected by temperature.

On the other hand, tadpoles of the Irschenhausen race reared at 20° C. gave 241 undifferentiated females, and 6 lots reared at 10° C. gave 25 ♂ and 438 ♀. From this result Witschi concludes that cold is a male determining factor, but it should not be overlooked that many of these so-called females would later develop into male frogs. In a later account of these experiments he states that "cold changes the males into protogynous juvenile hermaphrodites as is in general normal for undifferentiated races."

It seems questionable, therefore, whether there is anything more here than a retardation of the definitive male condition.

In so far as it is possible to reach a provisional conclusion from the evidence available at present, it appears that in the undifferentiated races the germ-cells, that are present in half the individuals that would normally become females, may be changed over into sperm-cells, or else be replaced by cells from a different source that, in turn, become sperm-cells. In other words, the balance of the

genes that ordinarily suffices in frogs to give males or females may be "overridden" by environmental factors and testes may develop in an individual whose internal chromosomal balance would produce a female. Stated in another way, this may mean that each frog is capable of developing both testes and ovary; that under normal circumstances the XX individual develops only the ovary

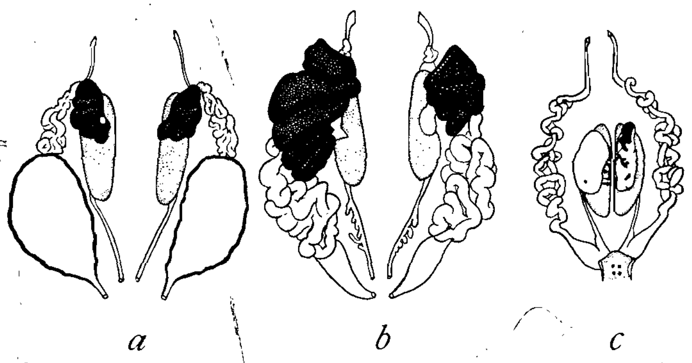


FIG. 146.
Three hermaphroditic frogs. (After Crew and Witschi.)

and the XY individual a testis, but under exceptional conditions a female of the XX type may develop a testis. The possibility of the reciprocal change has not been demonstrated.

There are many records of "hermaphrodite" adult frogs (Fig. 146). Crew has listed 40 recent cases. Whether these hermaphrodites are related in any way to the inversions just described is unknown. It is significant perhaps that a few individual hermaphrodites have also been reported from those experiments. On the other hand, it is possible that some of the hermaphrodites have a different origin. There is not much evidence that they can be explained as gynandromorphs or mosaics due to elimination

The Transformation of Bidder's Organ of the Male Toad into an Ovary.

The anterior part of the testis of the male toad is composed of rounded cells that resemble young egg-cells

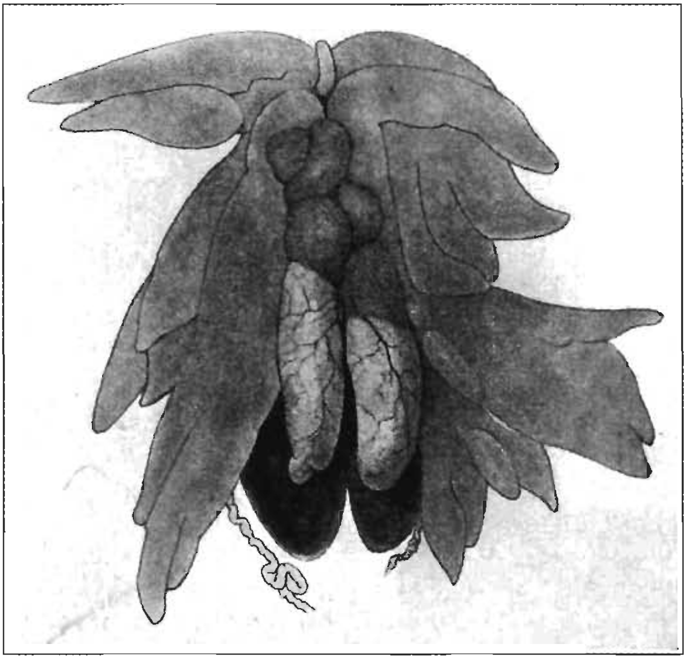


FIG. 147.

Bidder's organ at the anterior end of the testis of a half-grown male of a California species of Bufo. The lobes of the fat bodies lie at the sides, the kidney beneath. The testes are indicated by the branching blood vessels in their walls, the Bidder's organs lie in front of the testes each consisting of several lobes.

(Fig. 147). It is conspicuous in the young toad even before the germ-cells in the more posterior part or testis proper have differentiated. The anterior part is called Bidder's organ and has for many years excited the inter-

est of zoölogists, who have proposed many views as to its possible functions. The most frequent interpretation is that the Bidder's organ is an ovary and the resemblance of its cells to eggs lends strong support to this interpretation; but the presence of a Bidder's organ at the ante-

a b

FIG. 148.

Toad in third year from which the testes have been removed at an early stage. Bidder's organ has developed into an ovary. In the figure (to the right) the ovary is turned to one side in order to show the enlarged oviduct. (After Harms.)

rior end of the true ovary in the young female is difficult to bring into accord with the view that in the male the same organ is an ovary, for, if so, the female has a rudimentary or perhaps ancestral rudimentary ovary in front, and a functional one behind it.

The experimental work of Guyénot and Ponse (1923) and of Harms (1923, 1926) shows that when the testes are completely removed from a young toad, the organ of Bidder develops after two or three years into an ovary with

eggs (Fig. 148). The eggs have been deposited and fertilized and observed to develop. There can be here no doubt but that a female has arisen after removal of the testes, but whether the individual operated upon is to be called a male or an hermaphrodite is perhaps a question of definition. Personally, I should call the above toad a male, and interpret the result to mean that a male has been transformed into a female by removal of the testes. It seems to me a matter of secondary importance that the male toad carries an organ whose cells are potentially capable of developing into egg-cells, for, in general, even when sex is determined by a chromosomal mechanism, there is no implication that under changed conditions undifferentiated cells situated in that part of the body where the gonads develop might not become egg-cells even with the chromosomal complex that gives rise to a male under other circumstances. In terms of genes, this means that in the toad the balance of the genes is such that under the normal conditions of development one part of the gonad (the anterior end) begins to develop into an ovary, while another part (the posterior end) begins to develop into a testis. The latter overtakes the former as development proceeds and holds its further development in check. If the testicular end is removed, however, this control is lost, and the cells of Bidder's organ proceed to develop into functional eggs. Ponse, using eggs from a transformed male, obtained 9 sons and 3 daughters. Harms reared from a similar male 104 sons and 57 daughters. If it be assumed that the male toad is XY, then it is expected that the eggs of the transformed male will be X and Y in equal numbers. If now, these are fertilized by a normal male, the expected offspring will be 1XX+2XY+1YY. The YY-individuals probably fail to develop, leaving a ratio of two males to one female, which agrees closely with the actual results.

Champy has described a case of "total sexual inversion" in Triton alpestris. A male triton that had functioned as a fertile male was subsequently starved. Under these circumstances the normal renewal of the sperm does not take place, but the animal remains in a sort of "neutral condition," characterized by the presence in the testis of primitive germ-cells. It remains in this condition throughout the winter. Two male tritons that had been treated in this way, underwent, after they had been intensively renourished, a change in color from male to female. One of these examined several months later furnished evidence that Champy interprets as sex inversion. Since this case has been cited recently as furnishing complete evidence of sex inversion, it may be worth while to give a somewhat detailed statement as to what Champy really records. In place of the ovaries he found an elongated organ resembling somewhat a young ovary. When sectioned it was found to contain young egg-like cells ("ovocytes") resembling those of a young triton at the stage of metamorphosis. An oviduct was also apparent, recognizable by its white color and sinuous course. Champy concludes we have here an adult animal with the ovary of a young female. The evidence seems to indicate that the treatment led to the absorption of the spermatocytes and sperm. It does not indicate clearly whether the new cells that come to replace them are enlarged spermatogonia or primitive germ-cells or young ova. In the light of other evidence in the Amphibia (Witschi, Harms, Ponse) it may seem not improbable that these cells are in reality young egg-cells and that a partial inversion has taken place.

Sex Reversal in Miastor.

In flies belonging to the genera Miastor and Oligarces there is a generation consisting of sexual winged males

and females that appear at the end of a long succession of generations of maggots reproducing by parthenogenesis.

The eggs laid by the winged females are supposed to be fertilized by sperm from the winged males and develop as far as the maggot (larval) stage. These maggots, without passing on to the adult stage, produce eggs that develop by parthenogenesis. From these eggs a new generation of maggots arises that repeats the process. This continues throughout the year, the maggots living under the bark of dead trees, and in some species on mushrooms. In the spring or summer, winged males and females appear from eggs laid by the last generation of maggots. The appearance of the winged forms seems to be connected with some change in the environment. Recently Harris has shown that when the cultures become crowded, owing to the presence of many maggots, the adult insects appear if suitable conditions prevail, while if the maggots are reared in isolation, or in small numbers, they continue to reproduce in the larval stages (paedogenesis). The effective factors in crowding are not known. If young from a single individual maggot are reared together, and if their offspring in turn are kept in the same culture, etc., it has been found by Harris that when the adult flies appear they are of one sex in each such culture. This seems to mean that each individual maggot is either male or female in genetic constitution, and reproduces by parthenogenesis the same sex. If this is the correct conclusion, it follows that both the male-determined maggots and the female-determined maggots produce functional eggs. As yet we have no evidence relating to the distribution of the sex-chromosomes in these flies.

There is, here, an example of male-determined individuals producing parthenogenetic eggs at one phase of the life cycle and spermatozoa at another phase.

Sex Reversal in Birds.

It has long been known that old hens, and hens with ovarian tumors, may develop the secondary plumage of the male, and that they sometimes show characteristic male behavior. It was also known (Goodale) that after the complete removal of the single left ovary of a young chick, the bird, when mature, develops the secondary sexual characters of the male sex. Both effects may be interpreted on the hypothesis that the normal ovary of the hen produces some substance that suppresses the full development of the plumage. When the ovary is diseased or removed the hen then develops the full possibilities of her genetic composition as seen ordinarily only in the male.

It is also known that hermaphroditic fowls occur in which both ovaries and testes may be present, although neither, as a rule, is fully developed, and it may or may not be significant that in most of these cases the gonad contains a tumor. There is some doubt here whether the hermaphroditic condition came first, and the tumor later, or, the ovary of a normal hen becoming tumorous, a testis began later to develop. In none of these cases is there evidence of sex reversal in the sense that the bird functioned at one time as a female and later as a male. One case has, however, been recently reported by Crew (1923) in which a hen is said to have laid eggs and reared chicks (from them?) and later to have become a functional male that fertilized two eggs of a normal hen. Concerning the second part of the story there seems to be no question, since the results were obtained under controlled conditions, but the previous history of this hen is not perhaps above suspicion, since it was apparently an unrecorded member of a small flock and no evidence by direct observation or by trap nesting is given that she was known to

lay eggs. When killed the bird was found to have extensive tumor growths in the situation of the ovary. "Incorporated in the dorsal aspect of this mass, there was a structure exactly resembling a testis, while another, similar in appearance, was situated in like position on the other side of the body." Every stage of spermatogenesis was present in the testes. On the left side "a thin straight oviduct could be identified having a diameter of 3 mm. in its widest part near the cloaca."

A second case has been recorded by Riddle. A ring dove functioned first as a female, laying a series of eggs. She ceased later to lay eggs, and frequently acted as a male in courtship and copulation. Many months later she died with very advanced tuberculosis. She was opened and under misapprehension that she was her mate (a male that had died 17½ months earlier) was recorded as a male. Later, when her number and record were determined, it was found that she had been the female, but the "testes" had been thrown away. There is here no record that the bodies identified as testes contained sperm.

The Effect of Ovariotomy in Birds.

The complete removal of the single left ovary of young chicks is a rather difficult operation. In 1916 Goodale carried out several successful operations of this kind. The birds developed the full plumage of the male. Goodale also reported the presence on the right side of a rounded body with tubules which he compared with early nephrogenous tissue. Benoit has also recently described the effect of ovariotomy on young birds. In general, the effect on the plumage, comb, and spurs is the same as in Goodale's birds, but in addition he describes the development of a testis or testis-like organ in the *situs* of the rudimentary right "ovary," and sometimes a similar organ in the place of the left ovary removed. In one case germ-

cells in all stages of ripening and even spermatozoa (pycnotic) were found. This single case calls for careful scrutiny, since it is, so far, the only recorded case of the presence in the testis-like organs of spermatozoa, or even distinctive germ-cells. The left ovary had been removed from a bird twenty-six days after hatching. At six months its comb was red, turgid, stood upright, and was as large as that of a cock. An organ "resembling a testis had developed on the right side." Histologically it was found to contain seminiferous tubules containing all stages of spermatogenesis. The nuclei of the spermatids were pycnotic and the spermatozoa, few in number, appeared abnormal. The efferent canal of the male extended from this body to the cloaca. There was also present at the base of the testis a tubular structure resembling the epididymis of the young cock. The presence of spermatozoa in the testis-like organ is the only record of this kind. In the other birds operated on by Benoit, in which testis-like bodies developed, no germ-cells were found. May it not be possible that in the above case a mistake had been made and that the bird was in reality a male? It should be added that Benoit found, after removing its testis, the comb shrank and the bird came to resemble a capon. In other cases, no such decrease of the comb has been reported. Still, it is just possible that the presence of testis-like organs that were present with sperm in them may be held responsible for the full development of the comb and wattles. Another bird, ovariotomized at four days after hatching, described by Benoit, showed at four months an unusual organ. An examination revealed, on the right side, a testicle-like organ. No report of its contents is made.

Benoit examined the histological structure of the right rudimentary ovary of a young normal female. He describes it as identical with an epididymis of a young male

having efferent ciliated canals and "rete testis." He concluded that the right gonad of birds is not a rudimentary ovary, but a right rudimentary testis that enlarges when the left ovary is removed to become a testis. The evidence does not, I think, necessitate this conclusion, for it is known that in the early stage of development of the reproductive organs in vertebrates, the essential accessory organs of the male and the female are present in both sexes. It is possible, therefore, that upon interference with the normal process of development (removal of the left ovary) these rudimentary organs may begin to develop and produce a testis-like structure, which, in most cases so far reported, does not contain sperm-cells. The occurrence of globular organs (reported by Goodale and by Domm) on the *left side also* seems to support this view, rather than that advanced by Benoit.

A preliminary report of the results of ovariotomy in young birds has recently been given by L. V. Domm (1924). The birds when they become adult not only show secondary male characters in their plumage, comb, wattles, and spurs, but fight with normal cocks, crow, and attempt to tread hens. One bird had a "white testis-like organ" in the position of the normal ovary (removed). Associated with the organ was also a small ovarian follicle. On the right side there was also a testis-like organ. A second bird was similar as to its gonads. In a third bird a testis-like organ was present only on the right side. In none of these cases are germ-cells or spermatozoa reported as present.

Whether these cases are strictly sex reversals cannot be definitely stated, unless Benoit's observation on the presence of sperm is confirmed. Aside from this unique statement, the other results appear to show definitely that, after removal of the ovary, a structure develops resembling in its appearance a testis (except for the pres-

ence of germ-cells). The development of this organ, after castration, can, I think, be provisionally at least accounted for by a secondary growth and enlargement of the fundaments of the male organs that are known to be present in the embryonic stage. The maintenance of a testis, even a functional one, in a female body is not in itself surprising, since it is known that pieces of testis, grafted into the body of a female, may continue to develop, and even to produce sperm.

In general, it appears that the genetic composition of the female bird (present both in the body-cells and in the young ovary) creates a favorable situation for the development of the ovary, rather than a testis. Conversely, in the male the genetic composition is favorable for the development of the testis. In the male, however, the early removal of the testis does not suffice to call forth the development of structures peculiar to the ovary.

The Sex of Parabiotic Salamander Twins.

The union of young salamanders by side-to-side fusion has been brought about by several embryologists. The young embryos taken from the egg, just after closure of the medullary folds, have portions of one side of each removed and are then brought in contact by the exposed surface. Their union quickly follows. Burns has studied the sex of the united (parabiotic) twins. He found that members of a pair were always of the same sex; 44 pairs were both males, 36 pairs were both females. Random union would give 1 pair of males to 2 pairs of male-females to 1 pair of females. Since no double-sexed pairs appear, it follows either that pairs of opposite sexes die, or that the sex of one individual changes over that of the other and, since both male and female pairs were found, the influence is sometimes one way, sometimes the other way. Unless some explanation can be found for such a

difference in the reciprocal effects, the results do not convincingly demonstrate the probability of the latter interpretation.

Sex Reversal in Hemp.

Many of the flowering plants develop both pistils containing egg-cells and stamens containing pollen in the same flower, sometimes in different flowers on the same plant. It is not uncommon for the pollen to ripen before the ovules, or, in other cases, the ovules before the pollen. In other plants, the ovules may develop only on one plant, and the pollen on another plant, *i.e.*, the sexes are separate, the species dioecious. In some of these dioecious plants, however, the organs of the opposite sex may occur as rudiments; occasionally they become functional. Correns has studied a few cases of this kind, and has attempted to test the character of the germ-cells of such exceptional cases.

More recently experiments with dioecious hemp (Cannabis sativa) by Pritchard, Schaffner, and McPhee have shown that environmental conditions may change a pistil-producing plant (or female) into one in which stamens and even functional pollen are also produced, and, conversely, may change a staminate plant into one producing pistils containing functional eggs.

When hemp seeds are planted at the normal time in early spring they produce male (staminate) and female (carpellate) individuals in about equal numbers (Fig. 149), but Schaffner has found that when planted in rich soil accompanied by a changed light period, the plants show "sex reversal" in both directions. "The amount of reversal is approximately inversely proportional to the length of daylight." That the same environment should change carpellate into staminate, and staminate into carpellate plants is at first sight rather surprising, for

one might anticipate that identical conditions would tend to bring each toward a neutral or intermediate condition or one only toward the other. In fact, something like this seems to take place, for on a carpellate plant stamens

FIG. 149.
Female plant, to left, and male plant, to right, of hemp. (After Pritchard, in Journal of Heredity.)

appear; conversely, on a staminate plant, pistils may appear. It is in this sense, in the main, that "sex reversal" occurs, although there are other cases still in which a new branch of a pistillate plant may develop only stamens, and a new branch of a staminate plant develop only pistils. In these extreme cases "sex reversal" may almost be said to take place in those new parts that develop

under changed conditions. McPhee, who has also studied the effect of exposure to light for different lengths of time, has found that male plants may produce branches with pistils, and vice versa; but he points out that many intersexual flowers also appear as well as many abnormal flowers. He states "that the changes produced are in many cases relatively minor ones and a sweeping conclusion that genetic factors are in no way concerned with sex in these species is not warranted at the present time."

The question as to whether there is an internal sex-determining factor system—possibly chromosomal—in hemp, is at present unanswered, and as yet we have only an oral report by McPhee concerning the genetic evidence, but this report is significant. If the normal female hemp plant is homogametic (XX) and the male heterogametic, then we may expect when a female is transformed into a male (or more accurately produces functional pollen) that all the pollen grains will be alike as to their sex-determining properties, *i.e.*, such a male is homogametic. McPhee's oral report[5] supports this view. Conversely, if the male (XY) is transformed into a female, then two kinds of eggs are expected. This seems to be realized.

Correns had earlier reported somewhat similar results in other plants but the data relating to the kinds of gametes produced are not satisfactory. It is to be hoped that evidence will soon be available that bears on this question. Assuming, in the meantime, that there is an internal mechanism for sex-determination in hemp (possibly of the XX-XY type), there is nothing revolutionary in the discovery that sex reversal may take place through environmental agencies, and there is certainly nothing in these results that is, in principle, in contradiction to

[5] At the meeting of the Zoölogical Society, 1925.

the presence of a sex-chromosomal mechanism that is sex-determining. Such a mechanism is an agent that tips the scale one way or the other under a given set of environmental conditions. The mechanism has never been understood in any other way. It may be overborne by other agents that turn the scale without thereby losing its power to act in its usual way when the conditions return under which it is accustomed to work. No better example of this relation could we hope to find; if the tentative conclusions stated above are confirmed, namely, the change of a homogametic female into a homogametic male in a species in which the normal male is heterogametic. This, in fact, would furnish another convincing proof of the genetic explanation of sex-determination, and one that would be especially instructive for those who fail to understand the interpretation that geneticists place on this mechanism and on Mendelian phenomena in general.

Another plant, Mercurialis annua, has separate sexes but rarely a pistillate flower appears on a male plant, and, conversely, a staminate flower on a female plant. A male plant may have 25,000 male flowers and only from 1 to 47 pistillate flowers, while the staminate flowers on a female may be as 1 to 32.

Yampolsky has reported the sex of offspring produced from both these kinds of plants after self-fertilization. Offspring from selfed female plants are female or predominantly female. Offspring of selfed male plants are male or predominantly male.

It is not possible at present to give a satisfactory explanation of these results on the XX-XY formula unless rather arbitrary assumptions are made. For instance, if the female plant is XX, then all the pollen grains she produces should carry one X, hence all the offspring should be females, as was the case. But if the male plant is XY, half the mature eggs should be X and half Y. Simi-

larly for the pollen. Self-fertilization should then give 1 XX+2 XY+1 YY. If YY dies there should be one female to two male offspring. This, however, was not the result obtained. In order that the selfed male plants should produce only males it must be assumed that the X eggs die as gametes and the Y eggs only are functional. As yet there is no evidence either for or against this hypothesis. Until there is evidence bearing on this question the case must be left open.

CHAPTER XVIII

STABILITY OF THE GENE

IN what has been said, so far, it has been implied that the gene is a stable element in heredity, but whether it is stable in the sense that a chemical molecule is stable, or whether it is stable only because it fluctuates quantitatively about a persistent standard, is a question of theoretical and perhaps of fundamental importance.

Since the gene cannot be studied directly by physical or chemical methods, our conclusions concerning its stability must rest on deductions from its effects.

Mendel's theory of heredity postulates that the gene is stable. It assumes that the gene that each parent contributes to the hybrid remains intact in its new environment in the hybrid. A few examples will serve to recall the nature of the evidence for this conclusion.

The Andalusian race of poultry has white, black, and blue individuals. If a white bird is mated to a black one, the offspring are slate-colored or blue. If two of these blue-colored birds are mated, the offspring fall into three classes, black, blue, and white, in the proportion of 1 : 2 : 1. The gene for white and the gene for black separate in the blue hybrid. Half the mature germ-cells come to carry the black-producing element and half the white-producing element. Chance fertilization of any egg by any sperm will give the observed proportions 1 : 2 : 1 in the second filial generation.

The test of the correctness of the assumption that the germ-cells of the hybrids are of two kinds is as follows. If a blue hybrid is back-crossed to a pure white bird, half

the offspring will be blue and half white. If a blue hybrid is back-crossed to a pure black bird, half the chicks will be black and half blue. Both results are consistent with the postulate that the genes of the blue hybrid are pure, half for black and half for white. Their occurrence in the same cell has not resulted in contamination or mutual infection.

In the example just given the hybrid is unlike either parent and, in a sense, is intermediate between them. In the next example the hybrid is indistinguishable from one parent. If a black guinea pig is bred to a white one, the offspring are black. If these are inbred, the offspring are three blacks to one white. The extracted whites breed as true as the original race of whites. The white gene has not been contaminated by the black gene in their sojourn together in the hybrid.

In the next example a case is chosen in which the two original forms are much alike, and the hybrids, while intermediate to some degree, are so variable that, at the ends of the series, they overlap the parental types. The types differ in a pair of genes.

If an ebony Drosophila is bred to a sooty one, the offspring are, as stated, intermediate, but variable. If these are inbred, they produce an array of shades that give a practically continuous series. There are ways, however, of testing the grades. When this is done it is found that the array is made up of individuals that are pure for ebony, others that are hybrids, and others that are pure for sooty, in the ratio of 1:2:1. Here again we have evidence that the genes have not been mixed. The continuous series of shades is merely due to overlapping variability of the characters.

All this is simple and clear because we are dealing in each case with a single pair of genes that act as differentials. These cases serve to establish the principle at stake.

In practice, however, the actual conditions are not always so simple. Many types differ from each other in several genes, each of which has an effect on the same character. Consequently, when they are crossed simple ratios are not found. For example, if a race of corn with a short cob is crossed to a race with a long cob, the next generation has cobs of intermediate length. If these are inbred the following generation has cobs of all sizes. Some are as short as the cobs of one of the original races, others as long as the original long. These stand at the ends. Between them is a series of intermediate sizes. A test of the individuals of this generation shows that there are several pairs of genes that affect the size of the cob.

Height in man is another such case. A man may be tall because he has long legs, or because he has a long body, or both. Some of the genes may affect all parts, but other genes may affect one region more than another. The result is that the genetic situation is complex and, as yet, not unraveled. Added to this is the probability that the environment may also to some extent affect the end-product.

These are the multiple factor cases, and students of heredity are trying to determine in each cross how many factors are present. The results are complex only because several or many genes are involved.

It is this sort of variability that in the earlier days, before Mendel's discovery had been made known, supplied natural selection with the evidence on which that theory was based. This question will be considered later, but first must be described the great advance in our understanding of the limitations of the selection theory that was made in 1909 by Johannsen's brilliant work.

Johannsen carried out his experiments with a garden plant, the princess bean. This bean reproduces exclusively by self-fertilization. As a result of long-continued in-

breeding each individual has become homozygous. This means that the two members of each pair of genes are identical. Hence such material is suitable to carry out

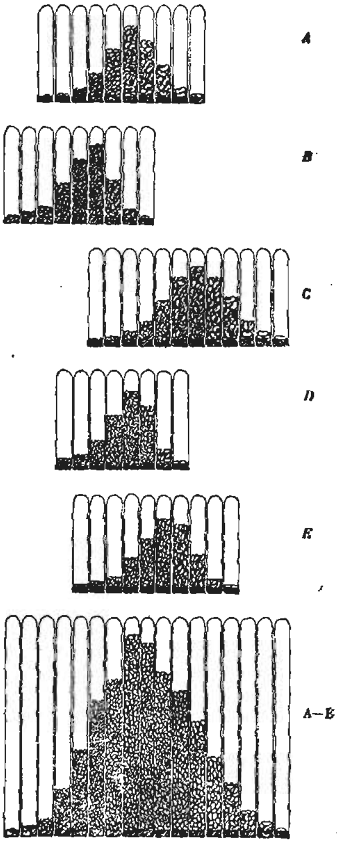


FIG. 150.

A-E groups of beans representing *five pure lines*. Below A-E the group formed of the combination of the other five. (After Johannsen.)

critical experiments to determine whether *individual* differences shown by the beans are affected by selection. If selection changes the character of the individual, it

must, under these conditions, do so by changing the gene itself.

The beans produced by each plant are somewhat variable in size, and when arranged according to sizes they give the normal curve of probability. All the beans from any one plant and all of the descendents of this plant have the same distribution (Fig. 150), no matter whether large beans are continually selected, or small beans are picked out in each generation. The offspring always give the same groups of beans.

Johannsen detected nine races of beans in those he examined. He interpreted his results to mean that the differences in size of the beans from a given plant are due to its environment in the widest sense. It was possible to demonstrate this with material in which the members of each pair of genes were identical when selection began. Selection is shown to have no effect in changing the genes themselves.

When sexually reproducing animals or plants are selected that are not homozygous at the start, the immediate outcome is different. There are numerous experiments showing what happens, such as Cuénot's results with spotted mice, or MacDowell's results with ear-length in rabbits, or East and Hayes' experiments with corn. Any of these might serve as an example of what takes place under selection. One example will suffice.

Castle studied the effects of selection of the color-pattern of a race of hooded rats (Fig. 151). Starting with the offspring of commercial animals, he selected in one direction those rats that had the broadest stripes, and in the other direction the rats that had the narrowest stripes, keeping these two lines apart. In the course of a few generations the two populations became measurably different—in one the dorsal stripe was broader, on the average, than in the original group of rats; in the other,

the stripe was narrower. Selection had in some way changed the width of the stripe. So far there is nothing in the results to show that this change may not have been due to the sorting out by selection of two sets of factors that determine the width of the dorsal stripe. Castle argued, however, that he was dealing with the effect of a

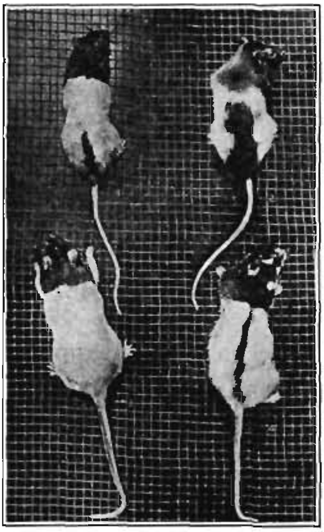


Fig. 151.
Four types of hooded rats. (After Castle.)

single gene, because when the striped rats are crossed to a rat with uniform coat (all black or all gray) and the hybrid (F_1) rats are inbred, their offspring give three uniform to one spotted coat. This Mendelian ratio does show, in fact, that a spotted coat is due to a recessive gene, but it does *not* show that the effects of this gene may not also be influenced by other genetic factors that determine the width of the stripe, and this is really the question at issue.

A later experiment, devised by Wright and carried out by Castle, showed, in fact, that the results had been due to the isolation of modifying genes for width of stripe. The test was as follows: Each of the highly selected races was back-crossed to wild rats, that is, rats with uniform coat color, and a second (extracted) generation of spotted rats obtained. The process was repeated with the (F_2) spotted rats obtained from the first back-cross. It was found after back-crossing for two or three generations that the selected stock began to change back, so to speak, to its original state. The selected race with a narrower stripe changed toward a broader stripe and the selected race with a broader stripe changed toward a narrower stripe. In other words, the two selected races became more and more like each other, and more like the original race from which they had started.

This result is completely in accord with the view that modifying factors are present in the wild rats that affect the width of the stripe in animals that are already striped. In other words, the original selection had changed the character of the stripe by sorting out those genes that made it broader or narrower.

At one time Castle went so far as to claim that the results of the experiments with hooded rats reëstablished a view that he ascribed to Darwin, namely, that selection itself brings about a change in the hereditary materials in the direction in which the selection takes place. If this were really Darwin's meaning, such an interpretation of variability might seem greatly to strengthen the theory of natural selection as the method by which evolution has taken place. Castle said in 1915: "All the evidence we have thus far obtained indicates that outside modifiers will not account for the changes observed in the hooded pattern, itself a clear Mendelian unit. We are forced to conclude that this unit itself changes under repeated

selection *in the direction of the selection;* sometimes abruptly, as in the case of our 'mutant' race, a highly stable plus variation; but much oftener gradually, as has occurred continuously in both the plus and the minus selection series."

In the following year he said: "Many students of genetics at present regard unit-characters as unchangeable. . . . For several years I have been investigating this question, and the general conclusion at which I have arrived is this, that unit-characters are modifiable as well as recombinable. Many Mendelians think otherwise, but this is, I believe, because they have not studied the question closely enough. The fact is unmistakable that unit-characters are subject to quantitative variation. . . . Selection, as an agency in evolution, must then be restored to the important place which it held in Darwin's estimation, an agency capable of producing continuous and progressive racial changes."

A careful reading of Darwin's books will fail to furnish a single clear statement to the effect that he believed that the selection process determines or influences the direction of future variation, unless we bring into the field another theory held by Darwin, namely, the theory of inheritance of acquired characters.

Darwin held strongly to the belief in Lamarck's theory. He did not hesitate to make use of it whenever his theory of natural selection was in difficulty. It would be logical, therefore, for anyone who cared to do so (although Darwin himself does not appear to have put the two views together, nor does Castle) to point out that whenever a more advantageous type is selected its germ-cells are exposed, so to speak, to the pangenes produced by its own body, and might be expected to be changed in the direction of the character selected. Hence each new advance would start from a new base, and if scattering variations

occurred about this as a new mode that overstepped the previous boundary, further advances would be expected to appear in the direction in which the last advance took place. In other words, selection would bring about further advances in the direction in which each selection had taken place.

But, as I have said, Darwin never made use of this argument in favor of his selection theory, although it might be claimed he did so in principle whenever he found natural selection inadequate to explain a situation and appealed to Lamarck's principle to carry through the new advance.

Today we regard the selection process, whether natural or artificial, as capable, at most, of causing changes only to the extent to which recombination of the genes already present may affect a change; or, in other words, selection cannot cause a group (species) to transcend the extreme variations that it naturally shows. Rigorous selection can bring a population to a point where all of the individuals are nearer to the extreme type shown by the original population, but beyond this it cannot go. Only by the occurrence of a new mutation in a gene, or by a mass-change in a group of old genes, is it possible, as it now appears to us, for a permanent advance—a step forward, or backward—to be made.

This conclusion is not only a logical deduction from the theory of the stability of the gene, but rests on numerous observations showing that whenever a population is subjected to selection, a rather rapid change begins, but quickly slows down and soon comes to a standstill at or near the extreme type shown by a few individuals of the original population.

So far the problem of the stability of the gene has been examined with respect to gene-contamination in the hybrid, and from the point of view of selection. The possible

influence of the body itself on the constitution of the gene has been only touched upon. The clean separation of the genes in the hybrid, that is the basal postulate of Mendel's first law, would not be possible if genes were subject to influences from the bodily characters of the hybrid.

This conclusion brings us face to face with the Lamarckian theory of the inheritance of acquired characters. It would take us too far afield to attempt to consider the varied claims of this theory, but I may be allowed to call attention to certain relations that would be expected, if, as this theory postulates, the germ-cells are affected by the body in the sense that a change in a character may bring about corresponding alterations in specific genes. A few examples will illustrate the essential facts.

When a black rabbit is bred to a white rabbit the hybrid young are black, yet the germ-cells produced in this hybrid are black- or white-producing, in equal numbers. The black hair of the hybrid has no influence on the white germ-cells. No matter how long the genes for white are carried by black hybrids, the white genes remain white.

Now if the white gene is interpreted as an entity of some sort, it should show, *if* the Lamarckian theory holds, some effect of the body character of the individual in which the gene is carried.

Suppose, however, the white gene is interpreted as the absence of the black gene. Then, of course, there is no reason for supposing that the black color of the hybrid could produce any influence on nothing. To anyone holding the presence and absence theory this argument against Lamarck's theory is not cogent.

There is, however, another line of approach that may be more to the point. A white four-o'clock, bred to a red one, produces an intermediate hybrid with pink-colored flowers (Fig. 5). If we interpret the white color as an absence, the red must be due to a presence. The color of

the flower of the hybrid—pink—is weaker than the red, and if the character affects the gene, the red-producing gene in this hybrid should be diluted by the color of the flower. No such effects here, or elsewhere, have been recorded. The red and the white genes separate in the pink hybrid without showing any somatic effects.

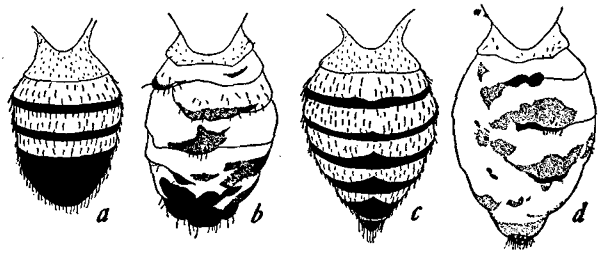


FIG. 152.

a, Abdomen of normal male; *b*, of "abnormal" male; *c*, of normal female; *d*, of "abnormal" female of Drosophila melanogaster.

The evidence from another source is perhaps even a stronger argument against the theory of the inheritance of acquired characters. There is a race of Drosophila—called abnormal abdomen—in which the regular banding of the abdomen is more or less obliterated (Fig. 152). This condition, in its most extreme form, appears in the first flies that emerge from a culture when the food is abundant and the culture is moist and acid. As the culture gets older and dryer, the flies that emerge become more and more normal in appearance, until at last they cannot be distinguished from wild flies. Here we have a genetic character that is extremely sensitive to the environment. Such characters as these furnish a favorable opportunity to study the possible effects of the body on the germ-cells.

If we breed the first hatched flies with very *abnormal*

abdomens, and at the same time and under like conditions we breed the late hatching flies with *normal* abdomens, we obtain exactly the same kinds of flies in the next generation. The first to emerge are abnormal, the later ones more normal. It has made no difference whether the abdomen of the parent was normal or abnormal, so far as the germ-cells are concerned.

If it be said that the effects might be too small to be seen at first, then I may add that late-hatching flies have been bred from for ten successive generations without any observed difference in the results.

Another example is equally convincing. There is a mutant stock of Drosophila called eyeless (Fig. 30). The eyes are smaller than the normal eye and very variable. By selection, a uniform stock has been produced in which most of the flies are without eyes, but, as each culture gets older, more and more flies have eyes, and larger ones. If, now, we breed from the late-hatched flies, the offspring are the same as when eyeless flies are used.

Here the presence of eyes in the older culture is a positive character and might be considered to furnish better evidence than the abnormal abdomen, where the symmetry and pigmentation of the late hatching larvae is less obviously a present character. The outcome is, however, the same in both cases.

It is quite unnecessary to attempt to consider here the numerous claimants that have appeared in the last few years, who have furnished "proof," as they say, of the inheritance of acquired characters. I choose only one case, that is the most complete of its kind, since it gives the numerical and quantitative data on which the conclusions are based. I refer to the recent work of Dürken. The experiment seems to have been carefully made and appears to Dürken to furnish proof of the inheritance of acquired characters.

Dürken worked with the chrysalids (or pupae) of the common cabbage butterfly (Pieris brassicae). Since 1890 it has been known that when the caterpillars of some butterflies pupate (that is, when they transform into the resting chrysalis) the color of the pupa is to some extent influenced by the background, or by the color of the light that falls on it.

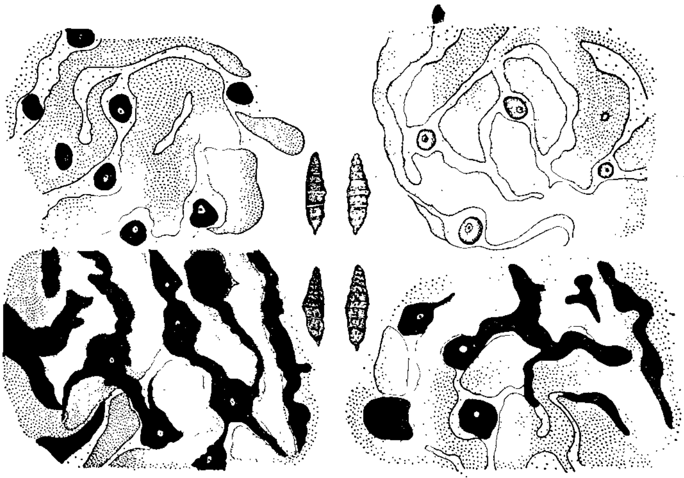


FIG. 153.

In the center four differently colored pupae of the cabbage butterfly. Around them is shown the characteristic arrangement of the pigment cells in the epidermis in different color types. (After Leonore Brecher.)

For example, the pupae of the cabbage butterfly are quite dark, if the caterpillars live and transform in daylight, or even in a faint light; but if the caterpillar lives in yellow or red surroundings or behind a yellow or red screen the pupae are green. The green color is due to the absence of superficial black pigment. In its absence the greenish yellow color of the interior shows through the skin (Fig. 153).

Dürken's experiments consisted in rearing caterpillars in orange (or red) light, where the pupae assumed a light or green color. The butterflies that emerged were reared in open cages and their eggs collected. Some of the young from these eggs were reared again in colored light, others in bright light or in darkness. The latter are the controls. The results are summarized in the chart (Fig. 154). The number of dark chrysalids is indicated by the length of the black band, and the green or light ones by the light band in the chart. As a matter of fact, the pupae were classified in five color groups. Three of these were then lumped together as dark and the other two as light.

As shown in Fig. 154 at 1 (which gives the normal coloration), nearly all pupae, collected at random or in normal surroundings, are dark; only a few are light or green. The caterpillars that came from these were reared in an orange environment. When they transformed into pupae there was a very high percentage of light-colored types, 2. If the light-colored types only are now picked out and reared, some in orange, some in the light, and others in the dark, the results are shown in 3a and 3b. In the former, there are more light pupae than before; since two generations have been in orange, the effect is augmented. It is the other set, 3b, however, that is more significant. As the bands show there were more light pupae than in the wild pupae, 1, that were reared in the light or dark. This increase Dürken attributes in part to the inherited effect of the orange light on the preceding generation, and in part to the new environment, whose effect is in the opposite direction.

Now this interpretation, from the point of view of genetics, is not satisfactory. The experiment shows, in the first place, that not all caterpillars respond to the orange light. If those that do respond are genetically different, then of course when they—the light pupae in the experi-

ment—are selected for the second orange trial and for the control in light and dark, we are dealing already with a more responsive type, a selected group, and these are expected to again respond in the next generation, as they do in fact.

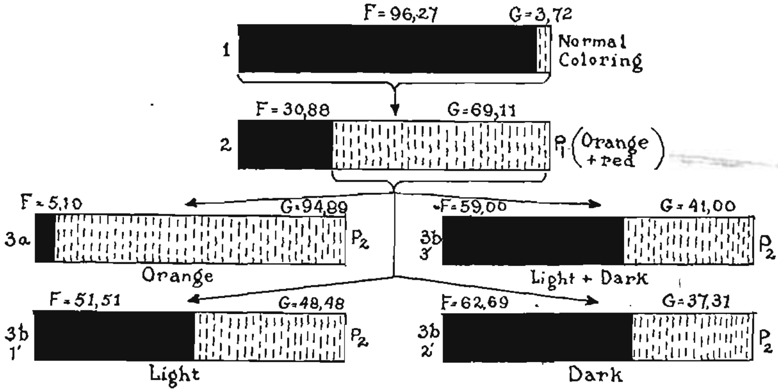


FIG. 154.

Diagram illustrating the results of selection of dark and light pupae of the cabbage butterfly. (After Dürken.)

Therefore, unless the material is genetically homogeneous at the start or unless other controls are used, the evidence fails signally to establish the inherited effect of the environment.

The same error runs through nearly all the work of this sort that has been done. Modern genetics, if it had accomplished nothing more, would have justified itself in showing the worthlessness of such evidence.

We may pass now to a group of cases in some of which it seems probable that the germ-cells themselves have been directly injured by special treatment, and that the injured germ-material is transmitted to later generations. Owing to this injury, malformations may appear in successive generations. This means that the treatment

has not affected the germ-material by first causing defects in the embryo, but has affected both the embryo and its germ-cells *at the same time.*

Stockard carried out a prolonged series of experiments on the effects of alcohol on guinea pigs. The guinea pigs were treated by placing them in closed tanks over strong

Fig. 155.
Two abnormal young guinea pigs whose ancestors were alcoholics. (After Stockard.)

alcohol. They breathed the air saturated with alcohol, and after a few hours became completely stupefied. The treatment was carried over a long time. Some of the guinea pigs were bred while undergoing treatment, others only at the end of the treatment. The results were essentially the same. Many young were aborted or absorbed, others were born dead, others showed abnormalities, especially in the nervous system and eyes (Fig. 155). Only those that themselves showed no defects could be bred. From these, abnormal young continued to appear

along with other individuals normal in appearance. In later generations abnormals continued to appear, but only from certain individuals.

If we examine the pedigrees of the alcoholic series there is no evidence that the results conform to any of the known Mendelian ratios. Moreover, the varied localization of the effects shown by the abnormals is not of a kind that resembles what we meet with when single gene-changes are involved. On the other hand, the defects have many points of resemblance to the kind of changes that we are familiar with in experimental embryology when abnormal development is brought about by treating eggs with toxic agents. Stockard has called attention to these relations, and interprets his result to mean that an injury of some sort to the germ-cells has been produced by the alcohol—an injury to some part of the machinery that is involved in heredity. The effects are localized only in so far as they pertain to those parts of the body that are most sensitive to any departure from the normal course of development. These parts are most frequently the nervous system and the sense organs.

More recently Little and Bagg have carried out a series of experiments on the effects of radium on pregnant mice and rats. When the treatment is properly administered, the young mice in uteró may develop abnormally. When examined before birth many of them show hemorrhagic areas (Fig. 156) in the brain and cord, or elsewhere (especially in the leg rudiments). Some of these embryos die before parturition, and are absorbed, others are aborted. Still others are born alive and some of these survive and may procreate. The offspring often show serious defects in the brain or in the appendages. One or both eyes may be defective. Both eyes may be absent, or one only may be present, much reduced in size. Bagg has bred some of these mice and finds that they produce many

abnormal offspring that show defects similar, in a general way, to those induced directly in the original embryos.

How shall we interpret these experiments? Has the radium first produced its effects on the brain of the de-

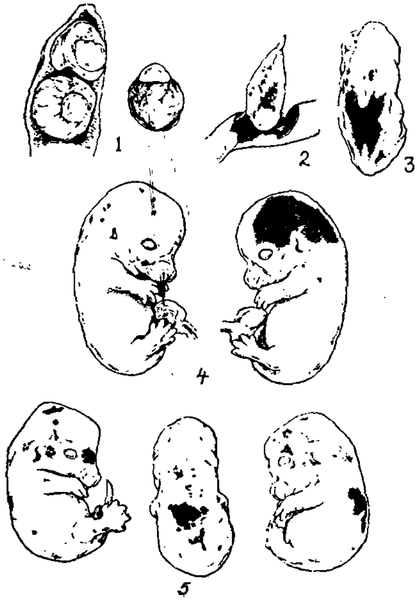


FIG. 156.

Young rat embryos with hemorrhagic areas whose mother had been treated with radium when the young were in utero. (After Bagg.)

veloping embryo, causing defects, and is it owing to the presence of these defects that the germ-cells of the same embryo become affected? There is an apparent objection to this interpretation. We should expect when the brain alone is affected, the next generation should show brain defects; when the eye is the principal organ affected, the next generation should show only eye defects. So far as

reported the results are not like this, for a mouse with abnormal brain and full-sized eyes may produce offspring that have defective eyes. In other words, there is not here a specific effect, but a general one.

The other interpretation is that the germ-cells of the young mouse in utero are affected by the radium. When, in turn, these germ-cells produce a new generation, the individuals are defective because the same organs whose normal development was most disturbed are the organs that are most easily affected by any alteration in the course of development. They are, in a word, the weakest or most delicately balanced phases of development, and therefore the first ones to show the effect of any departure from the normal course of events. This is, I think, at present the most plausible explanation of these and similar experiments.

CHAPTER XIX

GENERAL CONCLUSIONS

THE preceding chapters have dealt with two main topics: with the effects following a change in the number of the chromosomes; and with the effects following a change within a chromosome (a point mutation). The theory of the gene is broad enough to cover both these kinds of changes, although its main concern is with the gene itself. The term *mutation* also has come, through usage, to include the effects produced in both these ways.

These kinds of changes have important bearings on current genetic theories.

The Effects Produced by a Change in Chromosome Number and by a Change in a Gene.

When the number of the chromosomes is doubled, trebled, or multiplied any number of times, the individual has the same kinds of genes as before, and they stand in the same numerical ratio to one another. There is no *a priori* expectation that this kind of change would affect the character of the individual, were it not that the volume of the cytoplasm may not increase to correspond with the increase in the number of the genes. Just what a failure to attain a corresponding increase of cytoplasmic volume means is not clear at present. At any rate, the results show that triploid, tetraploids, octoploids, etc., do not differ markedly in any special characters (except size) from the original diploid type. In other words, the changes produced may be very numerous, but not strikingly different from the original ones.

On the other hand, the addition of a single chromosome or of two members of the same pair, or of two or more members of different pairs to the group, or the loss of a whole chromosome from the group, may be expected to produce more evident effects on the individual. There is some evidence that such additions or losses are less extreme when many chromosomes are present, or when the change takes place in a small chromosome. From the point of view of the theory of the gene, this result is what would be anticipated. For instance, the addition of one chromosome means that a large number of genes are now present in triplicate. The balance of the genes is changed in the sense that there are now present more genes of certain kinds than before, but since no new genes are added the effects would be expected to be distributed amongst many of the characters that might be somewhat enhanced or diminished in intensity. This accords with the facts as yet reported. It is interesting to note, however, that, as far as known, the general results are not beneficial but, if anything, deleterious. This, too, is expected if the adjustments, both to internal and to external relations, are as perfect as possible in the normal individual as its long evolutionary history might lead one to expect.

Because such a change affects many parts to a slight degree, it does not follow that such effects are more likely to lead to the establishment of a new viable type than when changes are brought about one step at a time by changes in single genes.

Furthermore, even the addition of two new chromosomes of the same kind, giving possibly a new stable type of inheritance, does not improve the situation, but, as far as we know,—the evidence is slight at present,—the maladjustments are even further increased. For these reasons it does not seem that a change from one chromo-

some group to another is easily brought about in this way, although the possibility of such a change cannot be entirely excluded. We need, at present, more evidence to decide this question.

The same arguments apply, though less strongly perhaps, to those cases when parts of chromosomes are added to, or subtracted from, the chromosome group. The effect produced is the same in kind, but less in degree, and it is correspondingly more difficult to determine whether the final effect on viability is injurious or beneficial.

The work of the last few years in genetics has made it clear that, despite the occurrence of the same number of chromosomes in related species and even in entire families and orders, it is hazardous to assume that the chromosomes, even in closely related species, are always identical as to their genes. The genetic evidence is beginning to make clear that readjustments may take place both within the chromosomes, where groups of genes may come to lie in reversed order, and between different chromosomes, where blocks of genes may be shifted, without giving a measurable difference in size. Even whole chromosomes might be recombined in different groupings without changing the actual number. Alterations of these kinds will affect profoundly the linkage relations, hence the modes of inheritance of the various characters, without, however, changing the total number or kinds of the genes involved. Unless, therefore, the cytological observations are checked by genetic studies it will always be unsafe to assume that identity in number of chromosomes means a correspondence in grouping of the genes.

Two methods by which changes in chromosome numbers take place are, first, the union of two chromosomes to form one, as in the attached X's of Drosophila, and the occasional breaking apart of chromosomes, as re-

ported by Hance in Oenothera and in several other cases. The temporary separation and reunion of certain chromosomes in moths, described by Seiler, also come under this heading, especially if, as he supposes, the separated elements may sometimes recombine reciprocally.

In contrast with the effect produced when large numbers of genes are involved, the effects produced by a change in a gene appear at first sight much more extreme. This first impression may, however, be very misleading. While it is true that many of the most striking mutant characters studied by geneticists are markedly different from the normal character with which they are contrasted, these mutant characters have often been chosen for study because they are sharply marked off from the typical character, and can, in consequence, be readily followed in succeeding generations. Their separation is accurate, and the results more certain than in cases where the differences are less marked, or where there is an overlap between the characters of the contrasted pair. Moreover, the more bizarre and extreme modifications, that sometimes amount to "abnormalities," are the ones that are most likely to attract attention and interest, hence are utilized for genetic study, while the less obvious modifications are overlooked or neglected. Geneticists are familiar with the fact that the more intensively any particular group is studied the more mutant characters are found which had been, at first, overlooked, and since these are those that more nearly approach the normal type, it becomes increasingly evident that the mutation process involves very small, as well as very great, modifications.

In the older literature the extreme, abnormal types were called sports, and for a long time it was supposed that these sports were sharply separated from the small or individual differences constantly present in all species

and commonly spoken of as variations. Today we know that there is no such sharp contrast, but that sports and variations may have the same kind of origin, and are inherited according to the same laws.

It is true that many of the small individual differences are due to the environmental conditions under which the development takes place, and superficial examination fails often to distinguish between this sort of variability and that due to minor changes brought about by genetic factors. One of the most important results of modern genetics is the recognition of this fact, and the invention of methods by which the smaller differences may be referred to one or to the other of these factors. If, as Darwin supposed, and if, as is generally accepted today, the process of evolution has taken place by the slow process of accumulation of small variations, it follows that it must be the genetic variations that are utilized, since these, and not those due to environmental effects, are inherited.

It must not be supposed, however, from what has just been said, that mutant changes produce only a single striking or even a single small change in one particular part of the body. On the contrary, the evidence from the Drosophila work, which is in accord with that from all other forms that have been critically studied, shows that even in those cases where one part is especially modified, other effects are commonly present in several or in all parts of the body. The subsidiary effects not only involve structural modifications, but physiological effects also, if one may judge by the activity, the fertility, and the length of life of the mutants. For example, the loss of positive phototropism, characteristic of Drosophila, accompanied a change involving a very slight alteration in the general color of the body.

The converse of this relation must also hold. Slight

changes due to a mutated gene that affect physiological processes and reactions may frequently be accompanied by alterations in external structural characters. If these physiological changes are of a kind to better adjust the organism to its environment, they may be expected to persist, and, at times, lead to the survival of new types. These types may then differ from the original type in superficial characters that are constant but trivial in themselves. Since many species differences appear to be of this kind, it is plausible to interpret their constancy as due not to their own survival value, but rather due to their relation to some other deeply seated character that is important for the welfare of the species.

In the light of what has just been said we can give a reasonable explanation of the differences that follow when a mutant change involves a whole chromosome (or part of one) and when only a single gene is involved. The former change adds nothing intrinsically new to the situation. More or less of what is already present is involved in the change, and the effects are small in degree but involve a large number of characters. The latter change—mutation in a single gene—may also produce widespread and slight effects, but, in addition, it often happens that one part of the body is changed to a striking degree along with other changes less striking. This latter kind of change, as I have said, supplies materials favorable for genetic study; these have been widely utilized. Now it is these mutational changes that have occupied the forefront of genetic publication, and have given rise to a popular illusion that each such mutant character is the effect of only one gene, and by implication to the fallacy, more insidious still, that each unit character has a single representative in the germ material. On the contrary, the study of embryology shows that every organ of the body is the end-result, the culmination of a long

series of processes. A change that affects any step in the process may be expected often to affect a change in the end-result. It is the final visible effect that we see, not the point at which the effect was brought about. If, as we may readily suppose, very many steps are involved in the development of a single organ, and if each of these steps is affected by the action of a host of genes, there can be no single representative in the germ-plasm for any organ of the body, however small or trivial that organ may be. Suppose, for instance, to take perhaps an extreme case, all the genes are instrumental in producing each organ of the body. This may only mean that they all produce chemical substances essential for the normal course of development. If now one gene is changed so that it produces some substance different from that which it produced before, the end-result may be affected, and if the change affects one organ predominatingly it may appear that one gene alone has produced this effect. In a strictly causal sense this is true, but the effect is produced only in conjunction with all the other genes. In other words, they are all still contributing, as before, to the end-result, which is different in so far as one of them is different.

In this sense, then, each gene may have a specific effect on a particular organ, but this gene is by no means the sole representative of that organ, and it has also equally specific effects on other organs, and, in extreme cases, perhaps on all the organs or characters of the body.

To return now to our comparison. The effect of a change in a gene (which if recessive means, of course, a pair of like genes) frequently produces a more localized effect than a doubling or trebling of the genes already present, because a change in one gene is more likely to upset the established relation between all the genes than is an increase in the number of genes already present. By extension, this argument seems to mean that each gene

has a specific effect on the course of development, and this is not inconsistent with the point of view urged above, that all the genes or many of them work together toward a definite and complicated end-product.

The best argument at present in favor of a specific action of each gene is found in the series of multiple allelomorphs. Here changes in the same locus affect primarily the same end-result not only in one organ, but in all the parts that are also visibly affected.

Is the Mutation Process Due to a Degradation of the Gene?

In his mutation theory de Vries spoke of types that we now call mutant recessive types as arising from the loss or inactivation of genes. Such changes he regarded as retrogressive. At about the same time, or a little later, the idea that recessive characters are due to losses of genes from the germ material became popular. At the present time several critics interested primarily in the philosophical discussion of evolution have attacked with violence the idea that the mutant types studied by geneticists have anything to do with the traditional theory of evolution. With this latter assertion we are not much concerned, and may safely leave the question at issue for the future to decide; but the suggestion that the mutation process, in so far as it involves an effect on single genes, is limited to the loss of genes or to their partial loss or degradation, as I venture to call such a change, is a matter of some theoretical interest; for, as Bateson elaborated in his 1914 address, it leads logically to the idea that the materials that we use in genetic work are due to loss of genes; that absences, in a literal sense, are the allelomorphs of wild type genes; and that, in so far as this evidence applies to evolution, it leads to the *reductio*

ad absurdum that that process has been a steady drain on the original storehouse of genes wherever they existed.

In chapter VI the genetic evidence at hand that bears on this question has been considered, and it is unnecessary to summarize again what was there said, but I may be allowed to repeat that it is not justifiable to conclude from the fact that many mutant characters are defective, or even partial or complete losses, that they must, therefore, be due to absences of a corresponding gene in the germ material. So far as there is any direct evidence that bears on this question, quite aside from the arbitrariness of the absence hypothesis, it does not, as I have attempted to show, support such a point of view.

There remains, however, a problem of some interest, namely, whether some or many of the changes in the genes that lead to the occurrence of mutant characters (whether recessive, intermediate, or dominant makes little difference) may not be due to a breaking up of a gene, or to its reconstitution into another element producing somewhat different effects. There is, however, no reason for assuming that such change, if it occurs, is a downhill one rather than the development of a more complex gene, unless it appears more probable, *a priori*, that a highly complex stable compound is more likely to break down than to build up. Until we know more concerning the chemical constitution of the genes, and how they grow and divide, it is quite futile to argue the merits of the two sides of the argument. For the genetic theory it is only necessary to assume that any kind of a change may suffice as a basis for what is observed to take place.

It is equally futile to discuss, at present, whether new genes arise independently of the old ones, and worse than futile to discuss how the genes arose in the first instance. The evidence that we have furnishes no grounds whatsoever for the view that new genes independently arise,

but it would be extremely difficult, if not impossible, to show that they do not arise. To the ancients it seemed not incredible that worms and eels arose from the river's slime, and that vermin in general arose in dark dusty corners. The origin of bacterial life from putrefying substances was believed in only one generation ago, and it was extremely difficult to prove that this does not happen. It may be equally difficult to prove convincingly, to one who insists on believing the contrary, that genes arise independently of other genes; but the genetic theory need not be anxious concerning this question until it meets with a situation where such a postulate becomes necessary. At present we find no need of interpolating new genes in the linkage series, or at the ends of the series. If the same number of genes is present in a white blood corpuscle as in all the other cells of the body that constitutes a mammal, and if the former makes only an amoeba-like cell and the rest collectively a man, it scarcely seems necessary to postulate fewer genes for an amoeba or more for a man.

Are Genes of the Order of Organic Molecules?

The only practical interest that a discussion of the question as to whether genes are organic molecules might have would relate to the nature of their stability. By stability we might mean only that the gene tends to vary about a definite mode, or we might mean that the gene is stable in the sense that an organic molecule is stable. The genetic problem would be simplified if we could establish the latter interpretation. If, on the other hand, the gene is regarded as merely a quantity of so much material, we can give no satisfactory answer as to why it remains so constant through all the vicissitudes of outcrossing, unless we appeal to mysterious powers of organization outside the genes that keep them constant. There is little

hope at present of settling the question. A few years ago I attempted to make a calculation as to the size of the gene in the hope that it might throw a little light on the problem, but at present we lack sufficiently exact measurements to make such a calculation more than a speculation. It seemed to show that the order of magnitude of the gene is near that of the larger-sized organic molecules. If any weight can be attached to the result it indicates, perhaps, that the gene is not too large for it to be considered as a chemical molecule, but further than this we are not justified in going. The gene might even then not be a molecule but only a collection of organic matter not held together in chemical combination.

When all this is given due weight it nevertheless is difficult to resist the fascinating assumption that the gene is constant because it represents an organic chemical entity. This is the simplest assumption that one can make at present, and since this view is consistent with all that is known about the stability of the gene it seems, at least, a good working hypothesis.

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BIBLIOGRAPHY

AIDA, T. 1921. On the inheritance of colour in a fresh-water fish, Aplocheilus latipes, etc. Genetics. VI.

ALLEN, C. E. 1917. A chromosome difference correlated with sex differences in Sphaerocarpos. Science. XLVI.

—— 1919. The basis of sex inheritance in Sphaerocarpos. Proc. Am. Phil. Soc. LVIII.

—— 1924. Inheritance by tetrad sibs in Sphaerocarpos. *Ibid.* LXIII.

ANDREWS, E. A. 1909. A male crayfish with some female organs. Am. Nat. XLIII.

D'ANGREMOND, A. 1914. *Parthenokarpie* und Samenbildung bei Bananen. Flora. CVII.

ARTOM, C. 1921. Il significato delle razze e delle specie tetraploidi e il problema della loro origine. Rivista di Biol. III.

—— 1921. Dati citologici sul tetraploidismo dell' Artemia salina di Margherita di Savoia (Puglia). R. Accademia Naz. dei Lincei, Roma. XXX.

—— 1924. Il tetraploidismo dei maschi dell' Artemia salina di Odessa in relazione con alcuni problemi generali di genetica. *Ibid.* XXXII.

BABCOCK, E. B., and COLLINS, J. L. 1920. Interspecific hybrids in Crepis. I. Crepis capillaris (L.) Wallr. x C. tectorum L. Univ. Calif. Publ. Agri. Sci. II.

BAEHR, W. B. v. 1920. Recherches sur la maturation des oeufs parthénogénétiques dans l'Aphis Palmae. La Cellule. XXX.

BAGG, H. J. 1922. Disturbances in mammalian development produced by radium emanation. Am. Jour. Anat. XXX.

—— 1923. The absence of one kidney associated with hereditary abnormalities in the descendants of X-rayed mice. Proc. Soc. Exp. Biol. and Med. XXI.

—— 1924. The absence of both kidneys associated with hereditary abnormalities in mice. *Ibid.* XXI.

BAGG, H. J., and LITTLE, C. C. 1924. Hereditary structural defects in the descendants of mice exposed to Roentgen-ray irradiation. Amer. Jour. Anat. XXXIII.

BAKER, J. R. 1925. On sex-intergrade pigs: their anatomy, genetics, and developmental physiology. Brit. Jour. Exp. Biol. II.

BALTZER, F. 1914. Die Bestimmung des Geschlechts nebst einer Analyse des Geschlechts-dimorphismus bei Bonellia Mitteil. Zool. Station Neapel. XXII.

—— 1920. Über die experimentelle Erzeugung und die Entwicklung von Triton-Bastarden ohne mütterliches Kernmaterial. Neuchatel Act. Soc. Helvét. Sci. Nat. XII.

—— 1922. Über die Herstellung und Aufzucht eines haploiden Triton taeniatus. Verh. Schweiz. Ges. Bern. CIII.

—— 1924. Über die Giftwirkung weiblicher Bonellia-Gewebe auf das Bonel-

lia-Männchen und andere Organismen und ihre Beziehung zur Bestimmung des Geschlects der Bonellienlarve. Natur. Gesell. in Bern. VIII.

BANTA, A. M. 1914. One hundred parthenogenetic generations of Daphnia without sexual forms. Proc. Soc. Biol. and Med. XI.

—— 1916. Sex intergrades in a species of crustacea. Proc. Nat. Acad. Sc. II.

—— 1916. A sex-intergrade strain of Cladocera. Proc. Soc. Exp. Biol. and Med. XIV.

—— 1917. A strain of sex intergrades. Anat. Rec. XI.

—— 1918. Sex and sex intergrades in Cladocera. Proc. Nat. Acad. Sc. IV.

BARTLETT, H. H. 1915. Additional evidence of mutation in Oenothera. Bot. Gaz. LIX.

—— 1915. The mutations of Oenothera stenomeres. Am. Jour. Bot. II.

—— 1915. Mutations en masse. Am. Nat. XLIX.

—— 1915. Mass mutation in Oenothera pratincola. Bot. Gaz. LX.

BATESON, W. 1913. Mendel's principles of heredity. 3d impression. Cambridge.

—— 1914. Address. Brit. Assn. Adv. Sc., Part I, Ref. 1; Part II, Ref. 66.

BATESON, W., and PUNNETT, R. C. 1905. Rep. Evol. Com. II.

—— 1911. On the interrelations of genetic factors. Proc. Roy. Soc., B. LXXXIV.

—— 1911. On gametic series involving reduplication of certain terms. Jour. Genet. I.

BATESON, W.; SAUNDERS, E. R.; PUNNETT, R. C.; HURST, C. C.; et al. 1902-1909. Reports (I to V) to the Evolution Committee of the Royal Society. London.

BAUR, E. 1911. Ein Fall von Faktorenkoppelung bei Antirrhinum majus. Verh. naturf. Ver. Brünn. XLIX.

—— 1912. Vererbungs- und Bastardierungsversuche mit Antirrhinum—II. Faktorenkoppelung. Zeit. Abst.-Vererb. VI.

—— 1914. Einführung in die experimentelle Vererbungslehre. Berlin.

BĚLAŘ, K. 1923. Über den Chromosomenzyklus von parthenogenetischen Erdnematoden. Biol. Zentralb. XLIII.

—— 1924. Neuere Untersuchungen über Geschlechtschromosomen bei Pflanzen. Zeit. Abst.-Vererb. XXXV.

BELLAMY, A. W. 1923. Sex-linked inheritance in the teleost Platypoecilus maculatus Günth. Anat. Rec. XXIV.

—— 1924. Bionomic studies on certain teleosts (Poeciliinae). Genetics, IX.

BELLING, J. 1921. The behavior of homologous chromosomes in a triploid canna. Proc. Nat. Acad. Sc. VII.

—— 1923. The attraction between homologous chromosomes. Eugenics, Genetics and the Family. I.

—— 1924. Detachment (elimination) of chromosomes in Cypripedium acaule. Bot. Gaz. LXXVIII.

BELLING, J., and BLAKESLEE, A. F. 1922. The assortment of chromosomes in triploid Daturas. Am. Nat. LVI.

—— 1923. The reduction division in haploid, diploid, triploid, and tetraploid Daturas. Proc. Nat. Acad. Sc. IX.

—— 1924. The distribution of chromosomes in tetraploid Daturas. Am. Nat. LVIII.

—— 1924. The configurations and sizes of the chromosomes in the trivalents of 25-chromosome Daturas. Proc. Nat. Acad. Sc. X.

BENOIT, J. 1923. Transformation expérimentale du sexe par ovariotomie précoce chez la Poule domestique. Compt. rend. l'Acad. Sciences. CLXXVII.

—— 1923. A propos du changement expérimental de sexe par ovariotomie, chez la Poule. Compt. rend. des séances d. la Société d. Biol. LXXXIX.

—— 1924. Sur la signification de la glande génitale rudimentaire droite chez la Poule. Compt. rend. l'Acad. Sciences. CLXXVIII.

—— 1924. Sur un nouveau cas d'inversion sexuelle expérimentale chez la Poule domestique. *Ibid.* CLXXVIII.

BENSAUDE, M. 1918. Recherches sur le cycle évolutif et la sexualité chez les Basidiomycetes. Nemours.

BERNER, O. 1924. Un coq asexuel. Rev. Fran. d'endocrin. II.

BLACKBURN, K. B. 1923. Sex chromosomes in plants. Nature. Nov. 10, 1923.

—— 1924. The cytological aspects of the determination of sex in dioecious forms of Lychnis. Brit. Jour. Exp. Biol. I.

—— 1925. Chromosomes and classification in the genus Rosa. Am. Nat. LIX.

BLACKBURN, K. B., and HARRISON, J. W. H. 1924. A preliminary account of the chromosomes and chromosome behaviour in the Salicaceae. Ann. of Bot. XXXVIII.

—— 1924. Genetical and cytological studies in hybrid roses. I. The origin of a fertile hexaploid form in the pimpinellifoliae-villosae crosses. Brit. Jour. Exp. Biol. I.

BLAKESLEE, A. F. 1921. Types of mutations and their possible significance in evolution. Am. Nat. LV.

—— 1921. The globe, a simple trisomic mutant in Datura. Proc. Nat. Acad. Sc. VII.

—— 1922. Variations in Datura, due to changes in chromosome number. Am. Nat. LVI.

—— 1924. Distinction between primary and secondary chromosomal mutants in Datura. Proc. Nat. Acad. Sc. X.

BLAKESLEE, A. F., and AVERY, B. T. 1919. Mutations in the jimson weed. Jour. Heredity. X.

BLAKESLEE, A. F., and BELLING, J. 1924. Chromosomal mutations in the jimson weed, Datura stramonium. *Ibid.* XV.

BLAKESLEE, A. F.; BELLING, JOHN; and FARNHAM, M. E. 1920. Chromosomal duplication and Mendelian phenomena in Datura mutants. Science. LII.

BLAKESLEE, A. F.; BELLING, JOHN; FARNHAM, M. E.; and BERGNER, A. D. 1922. A haploid mutant in the jimson weed, Datura stramonium. *Ibid.* LV.

BLEIER, H. 1925. Chromosomenstudien bei der Gattung Trifolium. Jahrb. wiss. Bot. LXIV.

BOEDIJN, K. 1924. Die typische und heterotypische Kernteilung der Oenotheren. *Zeit. f. Zell. w. Geweb.* I.

BONNIER, G. 1922. Double sex-linked lethals in Drosophila melanogaster. Acta Zool. III.

—— 1923. Studies on high and low non-disjunction in Drosophila melanogaster. Hereditas. IV.

—— 1923. Über die Realisierung verschiedener Geschlechtsverhältnisse bei Drosophila melanogaster. Zeit. Abst.-Vererb. XXX.

—— 1923. On different sex-ratios in Drosophila melanogaster. *Ibid.* XXXI.

—— 1924. Contributions to the knowledge of intra- and inter-specific relationships in Drosophila. Acta Zool. V.

BORING, A. M. 1923. Notes by N. M. Stevens on chromosomes of the domestic chicken. Science. LVIII.

BORING, A. M., and PEARL, R. 1918. Sex studies. XI. Hermaphrodite birds. Jour. Exp. Zoöl. XXV.

BOVERI, TH. 1888. Die Befruchtung und Teilung des Eies von Ascaris. Jena. Zeit. Med. Naturwiss. XXII.

—— 1908. Über die Beziehung des Chromatins zur Geschlechtsbestimmung. Sitz. Phys.-Med. Gesell. Würzburg.

—— 1909. Die Blastomerenkerne von Ascaris megalocephala und die Theorie der Chromosomen-Individualität. Arch. Zellf. III.

—— 1909. Über Geschlechtschromosomen bei Nematoden. *Ibid.* IV.

—— 1911. Über die Charaktere von Echiniden-Bastardlarven bei Hermaphroditismus. Verh. Phys.-Med. Gesell. Würzburg. XLI.

—— 1911. Über das Verhalten der Geschlechtschromosomen bei Hermaphroditismus. Beobachtungen an Rhabditis nigrovenosa. *Ibid.* XLI.

—— 1914. Über die Charaktere von Echiniden-Bastardlarven bei verschiedenem Mengenverhältnis mütterlicher und väterlicher Substanzen. *Ibid.* XLIII.

—— 1915. Über die Entstehung der Eugsterschen Zwitterbeinen. Arch. Entw.-mech. XLI.

BRAUN, H. 1909. Die spezifischen Chromosomenzahlen der einheimischen Arten der Gattung Cyclops. Arch. f. Zellf. III.

BRECKER, L. 1917. Die Puppenfärbung des Kohlweisslings, Pieris brassicae L. I-III. Arch. Entw.-mech. XLIII.

—— 1924. Die Puppenfärbungen des Kohlweisslings, Pieris brassicae L. VIII. *Ibid.* CII.

BREMER, G. 1922. A cytological investigation of some species and species hybrids within the genus Saccharum. Arch. van de Suikerindustrie in Nederlandsch-Indië.

—— 1923. A cytological investigation of some species and species hybrids within the genus Saccharum, I. II Genetica. V.

BRIDGES, C. B. 1913. Non-disjunction of the sex-chromosomes of Drosophila. Jour. Exp. Zoöl. XV.

—— 1914. Direct proof through non-disjunction that the sex-linked genes of Drosophila are borne by the X-chromosome. Science, n.s. XL.

—— 1915. A linkage variation in Drosophila. Jour. Exp. Zoöl. XIX.

—— 1916. Non-disjunction as proof of the chromosome theory of heredity. Genetics. I.

—— 1917. The elimination of males in alternate generations of sex-controlled lines. Anat. Rec. XI.

—— 1917. An intrinsic difficulty for the variable force hypothesis of crossing over. Amer. Nat. LI.

—— 1917. Deficiency. Genetics. II.

—— 1918. Maroon—a recurrent mutation in Drosophila. Proc. Nat. Acad. Sc. IV.

—— 1919. Duplications. Anat. Rec. XX.
—— 1919. The genetics of purple eye color in Drosophila melanogaster. Jour. Exp. Zoöl. XXVIII.
—— 1919. Specific modifiers of eosin eye color in Drosophila melanogaster. *Ibid.* XXVIII.
—— 1919. Vermilion-deficiency. Jour. Gen. Physiol. I.
—— 1919. The developmental stages at which mutations occur in the germ tract. Proc. Soc. Exp. Biol. and Med. XVII.
—— 1920. White-ocelli—an example of a "slight" mutant character with normal viability. Biol. Bull. XXXVIII.
—— 1920. The mutant crossveinless in Drosophila melanogaster. Proc. Nat. Acad. Sc. VI.
—— 1921. Gametic and observed ratios in Drosophila. Amer. Nat. LV.
—— 1921. Proof of non-disjunction for the fourth chromosome of Drosophila melanogaster. Science, n.s. LIII.
—— 1921. Current maps of the location of the mutant genes of Drosophila melanogaster. Proc. Nat. Acad. Sc. VII.
—— 1921. Genetical and cytological proof of non-disjunction of the fourth chromosome of Drosophila melanogaster. *Ibid.* VII.
—— 1921. Triploid intersexes in Drosophila melanogaster. Science, n.s. LIV.
—— 1925. Sex in relation to chromosomes and genes. Am. Nat. LIX.
—— 1925. Haploidy in Drosophila melanogaster. Proc. Nat. Acad. Sci. XI.
BRIDGES, C. B., and MORGAN, T. H. 1919. The second-chromosome group of mutant characters. Carnegie Inst. Wash. No. 278.
—— 1923. The third-chromosome group of mutant characters of Drosophila melanogaster. *Ibid.* No. 327.
BULLER, A. H. R. 1924. Experiments on sex in mushrooms and toadstools. Nature, CXIV.
CAROTHERS, E. E. 1913. The Mendelian ratio in relation to certain orthopteran chromosomes. Jour. Morph. XXIV.
—— 1917. The segregation and recombination of homologous chromosomes as found in two genera of Acrididae. *Ibid.* XXVIII.
—— 1921. Genetical behavior of heteromorphic homologous chromosomes of Circotettix (Orthoptera). *Ibid.* XXXV.
CASTLE, W. E. 1912. The inconstancy of unit-characters. Am. Nat. XLVI.
—— 1914. Size inheritance and the pure line theory. Zeit. Abst.-Vererb. XII.
—— 1916. Can selection cause genetic change? Am. Nat. L.
—— 1916. Further studies on piebald rats and selection with observations on gametic coupling. Carnegie Inst. Wash. No. 241, III.
—— 1919. Studies of heredity in rabbits, rats, and mice. *Ibid.* No. 288.
—— 1919. Is the arrangement of the genes in the chromosome linear? Proc. Nat. Acad. Sc. V.
—— 1919. Are genes linear or non-linear in arrangement? *Ibid.* V.
—— 1919. Does evolution occur exclusively by loss of genetic factors? Am. Nat. LIII.
CASTLE, W. E., and HADLEY, P. B. 1915. The English rabbit and the question of Mendelian unit-character constancy. Proc. Nat. Acad. Sci. I.
CASTLE, W. E., and PHILLIPS, JOHN C. 1914. Piebald rats and selection. Carnegie Inst. Wash. No. 195.

Castle, W. E., and Wachter, W. L. 1924. Variations of linkage in rats and mice. Genetics. IX.

Chambers, R. 1912. A discussion of Cyclops viridis Jurine. Biol. Bull. XXII.

Champy, C. 1921. Changement expérimental du sexe chez le Triton alpestris. Compt. rend. l'Acad. Sciences. CLXXII.

—— 1922. Étude expérimentale sur les différences sexuelles chez les Tritons: changement de sexe expérimental. Arch. d. morph. gén. et expér. VIII.

Chapin, C. C. 1917. A microscopic study of the reproductive system of foetal free-martins. Jour. Exp. Zoöl. XXIII.

Clausen, J. 1921. Studies in the collective species Viola tricolor L. I. II. Bot. Tidsskift. XXXVII.

—— 1924. Increase of chromosome numbers in Viola experimentally induced by crossing. Hereditas. V.

Clausen, R. E., and Goodspeed, T. H. 1916. Hereditary reaction-system relations—an extension of Mendelian concepts. Proc. Nat. Acad. Sc. II.

—— 1925. Interspecific hybridization in Nicotiana. II. A tetraploid glutinosa-tabacum hybrid, an experimental verification of Winge's hypothesis. Genetics, X.

Clausen, R. E., and Mann, M. C. 1924. Inheritance in Nicotiana Tabacum V. The occurrence of haploid plants in interspecific progenies. Proc. Nat. Acad. Sc. X.

Cleland, R. E. 1922. The reduction divisions in the pollen mother cells of Oenothera franciscana. Am. Jour. Bot. IX.

—— 1924. Meiosis in pollen mother cells of Oenothera franciscana sulfurea. Bot. Gaz. LXXVII.

Collins, E. S. 1919. Sex segregation in the Bryophyta. Jour. Genet. VIII.

—— 1920. The genetics of sex in Funaria hygrometrica. Proc. Roy. Soc. XCI.

—— 1920. Inbreeding and crossbreeding in Crepis capillaris (L.) Wallr. Univ. Calif. Pub. Agri. Sc. II.

Collins, J. L., and Mann, M. C. 1923. Interspecific hybrids in Crepis. II. A preliminary report on the results of hybridizing Crepis setosa Hall. with C. capillaris (L.) Wallr. and with C. biennis L. Genetics. VIII.

Correns, C. 1902. Über den Modus und den Zeitpunkt der Spaltung, etc. Bot. Zeit. LX.

—— 1909. Zur Kenntniss der Rolle von Kern und Plasma bei der Vererbung. Zeit. Abst.-Vererb. II.

—— 1916. Über den Unterschied von tierischem und pflanzlichem Zwittertum. Biol. Centralb. XXXVI.

—— 1920. Die geschlechtliche Tendenz der Keimzellen gemischtgeschlechtiger Pflanzen. Zeit. f. Bot. XII.

—— 1921. Versuche bei Pflanzen das Geschlechtsverhältnis zu verschieben. Hereditas. II.

Crew, F. A. E. 1921. A description of certain abnormalities of the reproductive system found in frogs, and a suggestion as to their possible significance. Proc. Roy. Phys. Soc. Edinburgh. XX.

—— 1921. Sex-reversal in frogs and toads. A review of the recorded cases of abnormality of the reproductive system and an account of a breeding experiment. Jour. Genet. XI.

—— 1923. Studies in Intersexuality. I. A peculiar type of developmental intersexuality in the male of the domesticated mammals. II. Sex-reversal in the fowl. Proc. Roy. Soc., B. XCV.

—— 1924. Hermaphroditism in the pig. Jour. Obstetrics and Gyn. Brit. Emp. XXXI.

CUÉNOT, L. 1898. L'hermaphroditisme protandrique d'Asterina gibbosa et ses variations suivant les localités. Zool. Anz. XXI.

—— 1902. La loi de Mendel et l'hérédité de la pigmentation chez les souris. Arch. zoöl. expér. et gén. (3). X.

—— 1903. L'hérédité de la pigmentation chez les souris (2). I. Hérédité de la pigmentation chez les souris noires. *Ibid.* (4). I.

—— 1904. L'hérédité de la pigmentation chez les souris (3). I. Les formules héréditaires. *Ibid.* (4). II.

—— 1905. Les races pures et leurs combinaisons chez les souris (4). *Ibid.* (4). III.

—— 1907. L'hérédité de la pigmentation chez les souris (5). *Ibid.* (4). VI.

DAVIS, B. M. 1909-1911. Cytological studies on Oenothera. Ann. of Bot. XXIII, XXIV, XXV.

—— 1910. Genetical Studies on Oenothera. Am. Nat. XLIV, XLV, XLVI, XLVII; Zeit. Abst.-Vererb. XII.

—— 1913. The problem of the origin of Oenothera Lamarckiana de Vries. New Phytol. XII.

—— 1924. The behavior of Oenothera neo-lamarckiana in selfed line through seven generations. Proc. Am. Phil. Soc. LXIII.

DELAGE, Y. 1903. L'hérédité, et les grands problèmes de la Biologie Générale. Paris.

DELAUNAY, L. 1915. Étude comparée caryologique de quelques espèces du genre Muscari Mill. Mém. de la soc. natur. de Kiew. XXV.

—— 1922. Comparative caryological study of species of Muscari and Bellevalia. Review of the Tiflis Bot. Garden, Series II, No. 1. (Russian.)

—— 1925. The S-chromosomes in Ornithogalum L. Science, LXII.

DELLA VALLE, P. 1907. Osservazione de tetradi in cellule somatiche, etc. Atti. Acc. Napoli, XIII.

DETLEFSEN, J. A. 1914. Genetic studies on a cavy species cross. Carnegie Inst. Wash. No. 205.

DETLEFSEN, J. A., and ROBERTS, E. 1921. Studies on crossing over. I. The effect of selection on crossover values. Jour. Exp. Zoöl. XXXII.

DIGBY, L. 1912. The cytology of Primula kewensis and of other related Primula hybrids. Ann. Bot. XXXVI.

DOMM, L. V. 1924. Sex-reversal following ovariotomy in the fowl. Proc. Soc. Exp. Biol. Med. XX.

DONCASTER, L. 1908. On sex inheritance in the moth, Abraxas grossulariata and its var. lacticolor. Fourth Rep. Evol. Com., Roy. Soc. London.

—— 1914. Chromosomes, heredity, and sex. Quar. Jour. Micr. Sc. LIX.

—— 1914. The determination of sex. Cambridge.

—— 1914. On the relations between chromosomes, sex-limited transmission, and sex-determination in Abraxas grossulariata. Jour. Genet. IV.

—— 1920. An introduction to the study of cytology. Cambridge.

DONCASTER, L., and RAYNOR, G. H. 1906. Breeding experiments with Lepidoptera. Proc. Zool. Soc. London, pp. 125-133.

DÜRKEN, B. 1923. Über die Wirkung farbigen Lichtes auf die Puppen des Kohlweisslings (Pieris brassicae) und das Verhalten der Nachkommen. Arch. f. Mikro. Anat. u. Entw.-mech. XCIX.

EAST, E. M. 1910. Notes on an experiment concerning the nature of unit characters. Science. XXXII.

—— 1911. The genotype hypothesis and hybridization. Am. Nat. XLV.

—— 1913. Inheritance of flower size in crosses between species of Nicotiana. Bot. Gaz. LV.

—— 1915. The chromosome view of heredity and its meaning to plant breeders. Am. Nat. XLIX.

—— 1916. Inheritance in crosses between Nicotiana Langsdorfii and N. alata. Genetics. I.

EAST, E. M., and HAYES, H. K. 1911. Inheritance in maize. Conn. Exp. Sta. Bull. No. 167.

—— 1912. Heterozygosis in evolution and in plant breeding. U.S. Dept. Agr., Bureau Plant Ind. Bull. No. 243.

—— 1914. A genetic analysis of the changes produced by selection in experiments with tobacco. Am. Nat. XLVIII.

EAST, E. M., and JONES, D. F. 1919. Inbreeding and outbreeding. Philadelphia.

EAST, E. M., and MANGELSDORF, A. J. 1925. A new interpretation of the hereditary behavior of self-sterile plants. Proc. Nat. Acad. Sci. XI.

EAST, E. M., and PARK, J. B. 1917. Studies in self-sterility. I. Genetics. II.

EMERSON, R. A. 1911. Genetic correlation and spurious allelomorphism in maize. Ann. Rep. Neb. Agr. Exp. Sta. No. 24.

—— 1914. The inheritance of a recurring somatic variation in variegated ears of maize. Am. Nat. XLVIII.

—— 1917. Genetical studies of variegated pericarp in maize. Genetics. II.

—— 1924. A genetic view of sex expression in the flowering plants. Science, LIX.

EMERSON, S. H. 1924. Do balanced lethals explain the Oenothera problem? Jour. Wash. Acad. Sc. XIV.

ERNST, A. 1918. Bastardierung als Ursache der Apogamie im Pflanzenreiche. Jena.

ESSENBERG, J. M. 1923. Sex-differentiation in the viviparous teleost Xiphophorus helleri Heckel. Biol. Bull. XLV.

—— 1926. Complete sex-reversal in the viviparous teleost Xiphophorus helleri. *Ibid.* LI.

FANKHAUSER, G. 1924. Analyse der physiologischen Polyspermie des Triton-Eies auf Grund von Schnürungsexperimenten. Jahrb. d. Phil. Fak. II. Universität Bern. V.

FARMER, J., and DIGBY, L. 1910. Cytological features of varietal and hybrid ferns. Ann. Bot. XXIV.

FAXON, W. 1881. Bull. Mus. Comp. Zoöl. VIII.

—— 1885. Mem. Mus. Comp. Zoöl. Harvard College. X.

—— 1898. Proc. U.S. Nat. Mus. XX.

FEDERLEY, H. 1913. Das Verhalten der Chromosomen bei der Spermatogenese der Schmetterlinge Pygaera anachoreta, curtula und pigra sowie einiger ihrer Bastarde. Zeit. Abst.-Vererb. IX.

—— 1914. Ein Beitrag zur Kenntnis der Spermatogenese bei Mischlingen

zwischen Eltern verschiedener systematischer Verwandtschaft. Ofversigt af Finska Vetenskaps-Societetens Förhandlingar. LVI.

FELL, H. B. 1923. Histological studies on the gonads of the fowl. I. The histological basis of sex reversal. Brit. Jour. Exp. Biol. I.

FICK, R. 1924. Einiges über Vererbungsfragen. Abhand. Preus. Akad. d. Wiss. Jahrg.

GATES, R. R. 1907. Pollen development in hybrids of Oenothera lata x O. Lamarckiana, and its relation to mutation. Bot. Gaz. XLIII.

—— 1913. Tetraploid mutants and chromosome mechanisms. Biol. Centralb. XXXIII.

—— 1915. On the modification of characters by crossing. Am. Nat. XLIX.

—— 1915. The mutation factor in evolution. London.

—— 1916. On pairs of species. Bot. Gaz. LXI.

—— 1917. Vegetative segregation in a hybrid race. Jour. Genet. VI.

—— 1923. Heredity and eugenics. London.

—— 1924. Polyploidy. Brit. Jour. Exp. Biol. I.

—— 1925. Species and chromosomes. Am. Nat. LIX.

GATES, R. R., and THOMAS, N. 1914. A cytological study of Oenothera mut. lata and Oe. mut. semilata in relation to mutation. Quar. Jour. Micr. Sc. LIX.

GEERTS, J. M. 1911. Cytologische Untersuchungen einiger Bastarde von Oenothera gigas. Ber. Deutsch. Bot. Gesell. XXIX.

GEINITZ, B. 1915. Über Abweichungen bei der Eireifung von Ascaris. Arch. Zellf. XIII.

GELEI, J. 1921-22. Weitere Studien über die Oögenese von Dendrocoelum. II. III. Arch. Zellf. XVI.

GIARD, A. 1886. De l'influence de certains parasites Rhizocephales sur les caractères sexuels extérieurs de leur hôte. C. R. Acad. Sc. Paris. CIII.

—— 1887. La castration parasitaire. Bull. Sc. Dép. Nord. XVIII.

—— 1887. Sur la castration parasitaire chez l'Eupagurus bernhardus et chez la Gebia stellata. C. R. Acad. Sc. Paris. CIV.

—— 1888. Sur la castration parasitaire chez les Eukyphotes des genres Palaemon et Hippolyte. *Ibid.* CVI.

—— 1888. La castration parasitaire (nouvelles recherches). Bull. Sc. Dép. Nord. I.

GOLDSCHMIDT, R. 1912. Erblichkeitsstudien an Schmetterlingen. I, 1. Zeit. Abst.-Vererb. VII.

—— 1912. Bemerkungen zur Vererbung des Geschlechtspolymorphismus. *Ibid.* VIII.

—— 1916. Experimental intersexuality and the sex problem. Am. Nat. L.

—— 1917. A further contribution to the theory of sex. Jour. Exp. Zoöl. XXII.

—— 1917. Crossing-over ohne Chiasmatypie? Genetics. II.

—— 1919. Intersexualität und Geschlechtsbestimmung. Biol. Zentralb. XXXIX.

—— 1920. Einführung in die Vererbungswissenschaft. Leipzig.

—— 1920, 1922, 1923. Untersuchungen über Intersexualität. I, II, III. Zeit. Abst.-Vererb. XXIII, XXIX, XXXI.

—— 1923. The mechanism and physiology of sex-determination. London.

GOODALE, H. D. 1911. Studies on hybrid ducks. Jour. Exp. Zoöl. X.

—— 1911. Some results of castration in ducks. Biol. Bull. XX.
—— 1911. Sex-limited inheritance and sexual dimorphism in poultry. Science. XXXIII.
—— 1913. Castration in relation to the secondary sexual characters of brown leghorns. Am. Nat. XLVII.
—— 1916. A feminized cockerel. Jour. Exp. Zoöl. XX.
—— 1916. Gonadectomy in relation to the secondary sexual characters of some domestic birds. Carnegie Inst. Wash. Pub. No. 243.
—— 1917. Crossing over in the sex-chromosome of the male fowl. Science, n.s. XLVI.
Goodspeed, T. H. 1913. On the partial sterility of Nicotiana hybrids made with N. sylvestris as a parent. Univ. Calif. Pub. Bot. V.
—— 1915. Parthenogenesis, parthenocarpy and phenospermy in Nicotiana. Univ. Calif. Pub. Bot. V.
—— 1923. A preliminary note on the cytology of Nicotiana species and hybrids. Svensk. Bot. Tidsk. XVII.
Goodspeed, T. H., and Ayres, A. H. 1916. On the partial sterility of Nicotiana hybrids made with N. sylvestris as a parent. II. Univ. Calif. Pub. Bot. V.
Goodspeed, T. H., and Clausen, R. E. 1917. The nature of the F_1 species hybrids between Nicotiana sylvestris and varieties of Nicotiana tabacum. Univ. Calif. Pub. Bot. V.
—— 1917. Mendelian factor differences versus reaction system contrasts in heredity. I and II. Am. Nat. LI.
—— 1922. Interspecific hybridization in Nicotiana. I. On the results of backcrossing the F_1 sylvestris-tabacum hybrids to sylvestris. Univ. Calif. Pub. Bot. XI.
Goodspeed, T. H., and Kendall, J. N. 1916. On the partial sterility of Nicotiana hybrids made with N. sylvestris as a parent. III. *Ibid.* V.
Gould, H. N. 1917. Studies on sex in the hermaphrodite mollusc Crepidula plana. I. History of the sexual cycle. Also II. Jour. Exp. Zoöl. XXIII.
Gowen, J. W. 1919. A biometrical study of crossing over. On the mechanism of crossing over in the third chromosome of Drosophila melanogaster. Genetics. IV.
Gowen, M. S., and Gowen, J. W. 1922. Complete linkage in Drosophila melanogaster. Amer. Nat. LVI.
Greenwood, A. W. 1925. Gonad grafts in embryonic chicks and their relation to sexual differentiation. Brit. Jour. Exp. Biol. II.
Gregory, R. P. 1909. Note on the histology of the giant and ordinary forms of Primula sinensis. Proc. Cambridge Phil. Soc. XV.
—— 1911. Experiments with Primula sinensis. Jour. Genet. I.
—— 1911. On gametic coupling and repulsion in Primula sinensis. Proc. Roy. Soc., B. LXXXIV.
—— 1912. The chromosomes of a giant form of Primula sinensis. Proc. Cambridge Phil. Soc. XVI.
—— 1914. On the genetics of tetraploid plants in Primula sinensis. Proc. Roy. Soc., B. LXXXVII.
Gudernatsch, J. F. 1911. Hermaphroditismus verus in man. Am. Jour. Anat. XI.

GUYÉNOT, E., and PONSE, K. 1923. Inversion expérimentale du type sexuel dans la gonade du crapaud. C. R. Soc. Biol. V.

HALDANE, J. B. S. 1919. The combination of linkage values, and the calculation of distances between the loci of linked factors. Jour. Genet. VIII.

HANCE, R. T. 1918. Variations in the number of somatic chromosomes in Oenothera scintillans. Genetics. III.

—— 1924. The somatic chromosomes of the chick and their possible sex relations. Science. LIX.

HANNA, W. F. 1925. The problem of sex in Coprinus lagopus. Ann. Bot. XXXIX.

HARGREAVES, E. 1914. The life history and habits of the greenhouse white fly. Ann. App. Bot. I.

HARMAN, M. T. 1917. Another case of Gynandromorphism. Anat. Rec. XIII.

HARMS, W. 1921. Untersuchungen über das Biddersche Organ der männlichen und weiblichen Kröten. I. Die Morphologie des Bidderschen Organs. Zeit. f. d. ges. Anat. LXII.

—— 1921. Verwandlung des Bidderschen Organs in ein Ovarium beim Männchen von Bufo vulgaris. Zool. Anz. LIII.

—— 1923. Untersuchungen über das Biddersche Organ der männlichen ånd weiblichen Kröten. II. Die Physiologie des Bidderschen Organs und die experimentellphysiologische Umdifferenzierung vom Männchen in Weibchen. Zeit. f. d. ges. Anat. LXIX.

—— 1923. Die physiologische Geschlechtsumstimmung. Verh. d. Deutsch. Zool. Gesells. E. V. XXVIII.

—— 1923. Körper und Keimzellen. Berlin.

—— 1924. Weitere Mitteilungen über die physiologische Geschlechtsumstimmung. Verh. d. Deutsch. Zool. Gesells. E.V. XXIX.

—— 1926. Beobachtungen über Geschlechtsumwandlung reifer Tiere und deren F_1—Generation. Zool. Anz. LXVII.

HARRIS, R. G. 1923. Occurrence, life-cycle, and maintenance, under artificial conditions, of Miastor. Psyche. XXX.

—— 1924. Sex of adult Cecidomyidae (Oligarces sp.) arising from larvae produced by Paedogenesis. *Ibid.* XXXI.

HARRISON, J. W. H. 1919. Studies in the hybrid Bistoninae. III. The stimulus of heterozygosis. Jour. Genet. VIII.

—— 1919. Studies in the hybrid Bistoninae. IV. Concerning the sex and related problems. *Ibid.* IX.

HARRISON, J. W. H., and BLACKBURN, K. 1921. The status of the British rose forms as determined by their cytological behavior. Ann. Bot. XXXV.

HARRISON, J. W. H., and DONCASTER, L. 1914. On hybrids between moths of the geometrid sub-family Bistoninae, with an account of the behavior of the chromosomes in gametogenesis in Lycia (Biston) hirtaria, Ithysia (Nyssia) zonaria and in their hybrids. Jour. Genet. III.

HARTMAN, C. G. 1920. The free-martin and its reciprocal. Science. LII.

HARTMAN, C. G., and HAMILTON, W. F. 1922. A case of true hermaphroditism in the fowl. Jour. Exp. Zoöl. XXXVI.

HARTMANN, M. 1923. Über sexuelle Differenzierung und relative Sexualität. Studia Mendeliana. Brünn.

—— 1925. Untersuchungen über relative Sexualität. I. Versuche an Ectocarpus siliculosus. Biol. Zentralb. XLV.

Harvey, E. B. 1916. A review of the chromosome numbers in the Metazoa. I. Jour. Morph. XXVIII.

—— 1920. A review of the chromosome numbers in the Metazoa. II. *Ibid.* XXXIV.

Heilborn, O. 1922. Die Chromosomenzahlen der Gattung Carex. Svensk. Bot. Tidskr. XVI. .

—— 1924. Chromosome numbers and dimensions, species-formation and phylogeny in the genus Carex. Hereditas. V.

Henking, H. 1892. Untersuchungen über die ersten Entwicklungsvorgänge in den Eiern der Insekten. Zeit. f. wiss. Zool. LIV.

Heribert-Nilsson, N. 1912. Die Variabilität der Oenothera Lamarckiana und das Problem der Mutation. Zeit. Abst.-Vererb. VIII.

—— 1920. Zuwachsgeschwindigkeit der Pollenschläuche und gestörte Mendelzahlen bei Oenothera Lamarckiana. Hereditas. I.

—— 1920. Kritische Betrachtungen und faktorielle Erklärung der Laeta-Velutinaspaltung bei Oenothera. *Ibid.* I.

Hertwig, G. 1911. Radiumbestrahlung unbefruchteter Froscheier und ihre Entwicklung nach Befruchtung mit normalem Samen. Arch. Mikr. Anat. LXXVII.

—— 1912. Das Schicksal des mit Radium bestrahlten Spermachromatins im Seeigelei. *Ibid.* LXXIX.

—— 1913. Parthenogenesis bei Wirbeltieren, hervorgerufen durch artfremden radiumbestrahlten Samen. *Ibid.* LXXXI.

Hertwig, O. 1911. Die Radiumkrankheit tierischer Keimzellen. Bonn.

—— 1911. Mesothoriumversuche an tierischen Keimzellen, ein experimenteller Beweis für die Idioplasmanatur der Kernsubstanzen. Sitz.-ber. Akad. Wiss. Berlin. XL.

—— 1911. Die Radiumkrankheit tierischer Keimzellen. Ein Beitrag zur experimentellen Zeugungs-und Vererbungslehre. Arch. Mikr. Anat. LXXVII.

—— 1913. Versuche an Tritoneirern über die Einwirkung bestrahlter Samenfäden auf die tierische Entwicklung. *Ibid.* LXXXII.

Hertwig, O. and G. 1923. Allgemeine Biologie. 6 and 7, Aufl. Jena.

Hertwig, P. 1920. Haploide und diploide Parthenogenese. Biol. Centralb. XL.

Hertwig, R. 1905. Über das Problem der sexuellen Differenzierung. Verhandl. Deutsch. Zool. Ges. XV.

—— 1906. Eireife und Befruchtung. O. Hertwig Handbuch d. Vergl. und Experim. Entwickelungslehre. I. Jena. 1909.

—— 1907. Weitere Untersuchungen über das sexualitätsproblem. III. Verh. d. Deutsch. Zool. Gesells. XVII.

—— 1912. Über den derzeitigen Stand des Sexualitätsproblems nebst eigenen Untersuchungen. Biol. Centralb. XXXII.

—— 1921. Über den Einfluss der Überreife der Eier auf das Geschlechtsverhältnis bei Fröschen und Schmetterlingen. Sitzungsb. d. k. bayer Akad. Wiss. (Math.-phys. Kl.) XXII.

Hindle, E. 1917. Notes on the biology of Pediculus humanus. Parasitology, IX.

HIRATA, K. 1924. Sex reversal in hemp. (Preliminary report.) Jour. Soc. Agri. and forestry, XVI.

HOVASSE, R. 1922. Contribution a l'étude des Chromosomes. Variation du nombre et régulation en parthénogenèse. Bull. Biologique de la France et de la Belgique. LVI.

HURST, C. C. 1925. Experiments in Genetics. Cambridge University Press.

HUXLEY, J. S. 1920. Note on an alternating preponderance of males and females in fish, and its possible significance. Jour. Genet. X.

HUXLEY, J. S., and CARR-SAUNDERS, A. M. 1924. Absence of prenatal effects of lens-antibodies in rabbits. Brit. Jour. Exp. Biol. I.

JANSSENS, F. A. 1905. Evolution des auxocytes mâles du Batrachoseps attenuatus. La Cellule. XXII.

—— 1909. La théorie de la chiasmatypie. Nouvelle interprétation des cinèses de maturation. *Ibid.* XXV.

JEFFREY, E. C. 1925. Polyploidy and the origin of species. Am. Nat. LIX.

JENNINGS, H. S. 1911. Pure lines in the study of genetics in lower organisms. Am. Nat. XLV.

—— 1918. Disproof of a certain type of theories of crossing over between chromosomes. *Ibid.* LII.

—— 1923. Crossing over and the theory that the genes are arranged in serial order. Proc. Nat. Acad. Sc. IX.

—— 1923. The numerical relations in the crossing over of the genes, with a critical examination of the theory that the genes are arranged in a linear series. Genetics. VIII.

JOHANNSEN, W. 1909. Elemente der exakten Erblichkeitslehre. Jena.

—— 1911. The genotype conception of heredity. Am. Nat. XLV.

JONES, D. F. 1917. Dominance of linked factors as a means of accounting for heterosis. Genetics. II.

JUNKER, H. 1923. Cytologische Untersuchungen an den Geschlechtsorganen der halbzwitterigen Steinfliege Perla marginata. Arch. Zellf. XVII.

JUST, G. 1925. Untersuchungen über Faktorenaustausch. Zeit. Abst.-Vererb. XXXVI.

KAHLE, W. 1908. Paedogenesis bei Cecidomyiden. Zoologica. Leipzig. LVIII.

KARPETSCHENKO, G. D. 1925. Karyologische Studien über die Gattung Trifolium L. Bull. Applied Bot. and Plant Breeding, XIV.

—— 1927. The production of polyploid gametes in hybrids. Hereditas, IX.

KIHARA, H. 1919. Über cytologische Studien bei einigen Getreidearten. I. II. Chromosomenzahlen und Verwandtschaftsverhältnisse unter Avena-Arten. Bot. Mag. Tokyo. XXXII. XXXIII.

—— 1921. Über cytologische Studien bei einigen Getreidearten. *Ibid.* XXXV.

—— 1924. Cytologische und genetische Studien bei wichtigen Getreidearten mit besonderen Rücksicht auf das Verhalten der Chromosomen und die Sterilität in den Bastarden. Memoirs Coll. Sc. Kyoto Imp. Univ., Series B. I.

KIHARA, H., and ONO, T. 1923. Cytological studies on Rumex L. I. Chromosomes of Rumex acetosa L. Bot. Mag. Tokyo, XXXVII.

—— 1923. Cytological studies on Rumex L. II. On the relation of chromosome number and sexes in Rumex acetosa L. *Ibid.* XXXVII.

—— 1925. The sex-chromosomes of Rumex acetosa. Zeit. Abst.-Vererb. XXXIX.

KNEIP, H. 1921. Über morphologische und physiologische Geschlechtsdifferenzierung. Verhandl. der Physikal-Med. Gesell. Würzburg. XLVI.

—— 1922. Über Geschlechtsbestimmung und Reduktionsteilung. *Ibid.* XLVII.

—— 1923. Über erbliche Änderungen von Geschlechtsfaktoren bei Pilzen. Zeit. Abst.-Vererb. XXXI.

KOJIMA, H. 1925. On the meiosis and the chromosome number in different races of Solanum Melongena L. Bot. Mag. Tokyo, XXXIX.

KORNHAUSER, S. I. 1919. The sexual characteristics of the membracid, Thelia bimaculata (Fabr.). Jour. Morph. XXXII.

KRAFKA, JR., J. 1920. The effect of temperature upon facet number in the bar-eyed mutant of Drosophila. I. II. III. Jour. Gen. Physiol. II.

—— 1920. Environmental factors other than temperature affecting facet number in the bar-eyed mutant of Drosophila. *Ibid.* III.

KUSCHAKEWITSCH, S. 1910. Die Entwicklungsgeschichte der Keimdrüsen von Rana esculenta. Festschr. f. R. Hertwig. II.

KUWADA, Y. 1919. Die Chromosomenzahl von Zea Mays L. Jour. Coll. Sc. Tokyo Imp. Univ. XXXIX.

LANCEFIELD, D. E. 1922. Linkage relations of the sex-linked characters in Drosophila obscura. Genetics. VII.

LANCEFIELD, R. C., and METZ, C. W. 1922. The sex-linked group of mutant characters in Drosophila willistoni. Am. Nat. LVI.

LANG, A. 1904. Über Vorversuche zu Untersuchungen über die Varietatenbildung von Helix hortensis Müller und Helix nemoralis L. Abdruck aus der Festschrift z. siebzigsten Geburtstage v. E. Haeckel. Jena.

—— 1908. Über die Bastarde von Helix hortensis Müller und Helix nemoralis. Jena.

—— 1911. Fortgesetzte Vererbungsstudien. I. Albinismus bei Bänderschnecken. Zeit. Abst.-Vererb. V.

—— 1912. Vererbungswissenschaftliche Miszellen. *Ibid.* VIII.

LILLIE, F. R. 1916. The theory of the free-martin. Science, n.s. XLIII.

—— 1917. The free-martin; a study of the action of sex-hormones in the foetal life of cattle. Jour. Exp. Zoöl. XXIII.

LIPSCHÜTZ, A. 1919. Die Pubertätsdrüse und ihre Wirkungen. Bern.

LITARDIÈRE, R. DE. 1925. Sur l'existence de figures didiploïdes dans le méristeme radiculaire du Cannabis sativa L. La Cellule, XXXV.

LITTLE, C. C. 1913. Experimental studies of the inheritance of color in mice. Carnegie Inst. Wash. No. 179.

—— 1914. Dominant and recessive spotting in mice. Am. Nat. XLVIII.

LITTLE, C. C., and BAGG, H. J. 1923. A brief description of abnormalities observed in the descendants of X-rayed mice. Anat. Rec. XXIV.

—— 1924. The occurrence of four inheritable morphological variations in mice and their possible relation to treatment with X-rays. Jour. Exp. Zoöl. XLI.

LJUNGDAHL, H. 1922. Zur Zytologie der Gattung Papaver. Svensk Bot. Tidskr. XVI.

—— 1924. Über die Herkunft der in der meiosis konjugierenden Chromosomen bei Papaver-Hybriden. Svensk Bot. Tidsk., XVIII.

LOCK, R. H. 1906. Recent progress in the study of variation, heredity and evolution. London and New York.

LONGLEY, A. E. 1923. Cytological studies in the genera Rubus and Crataegus. Am. Nat. LVII.

—— 1924. Chromosomes in maize and maize relatives. Jour. Agri. Research. XXVIII.

—— 1925. Segregation of carbohydrates in maize-pollen. Science. LXI.

LONGLEY, A. E., and DARROW, G. M. 1924. Cytological studies of diploid and polyploid forms in raspberries. Jour. Agri. Research. XXVII.

LOTSY, J. P. 1913. Hybrides entre espèces d'Antirrhinum. Repts. 4th Intern. Conf. Genet. Paris.

—— 1916. Evolution by means of hybridization. The Hague.

LUTZ, A. M. 1907. A preliminary note on the chromosomes of Oenothera Lamarckiana and one of its mutants, O. gigas. Science, XXVI, pp. 151-152.

—— 1912. Triploid mutants in Oenothera. Biol. Centralb. XXXII.

—— 1917. Fifteen- and sixteen-chromosome Oenothera mutants. Am. Jour. Bot. IV.

MAGNUSSON, H. 1918. Geschlechtslose Zwillinge. Eine gewöhnlich Form von Hermaphroditismus beim Rinde. Arch. f. Anat. u. Physiol. Anat. Abt.

MALLOCH, W. S. and F. W. 1924. Species crosses in Nicotiana, with particular reference to N. longiflora x N. Tabacum, N. longiflora x N. Sanderae, N. Tabacum x N. glauca. Genetics. IX.

MANN, M. C. 1923. The occurrence and hereditary behavior of two new dominant mutations in an inbred strain of Drosophila melanogaster. Genetics. VIII.

—— 1923. A demonstration of the stability of the genes of an inbred stock of Drosophila melanogaster under experimental conditions. Jour. Exp. Zoöl. XXXVIII.

—— 1925. Chromosome number and individuality in the genus Crepis. I. A comparative study of the chromosome number and dimensions of nineteen species. Univ. Calif. Pub. Agri. Sc., II.

MARCHAL, ÉM. 1912. Recherches cytologiques sur le genre Amblystegium. Bull. de la Soc. roy. de Bot. de Belg. LI.

MARCHAL, ÉL. and ÉM. 1906. Recherches Expérimentales sur la Sexualité des Spores chez les Mousses dioïques. Mém. couronnés, par la Classe des sciences, dans la séance du 15 décembre 1905.

—— 1907, 1911, and 1919. Aposporie et sexualité chez les mousses. Bull. de l'Acad. roy. de Belg. (Classe de science). Nos. 7, 9-10, 1.

MARÉCHAL, J. 1907. Sur l'Ovogénèse des Sélaciens et de quelques autres Chordates. I. Morphologie de l'Element chromosomique dans l'Ovocyte I chez les Sélaciens, les Téléostéens, les Tuniciers et l'Amphioxus. La Cellule. XXIV.

MARSHALL, W. W., and MULLER, H. J. 1917. The effect of long-continued heterozygosis on a variable character in Drosophila. Jour. Exp. Zoöl. XXII.

MAVOR, J. W. 1923. An effect of X-rays on crossing-over in Drosophila. Proc. Soc. Exp. Biol. and Med. XX.

—— 1923. An effect of X-rays on the linkage of Mendelian characters in the first chromosome of Drosophila. Genetics. VIII.

MAY, H. G. 1917. The appearance of reverse mutations in the bar-eyed race of Drosophila under experimental control. Proc. Nat. Acad. Sc. III.

—— 1917. Selection for higher and lower facet numbers in the bar-eyed race of Drosophila and the appearance of reverse mutations. Biol. Bull. XXXIII.

McCLUNG, C. E. 1902. The accessory chromosome—sex determinant? Biol. Bull. III.

—— 1902. Notes on the accessory chromosome. Anat. Anz. XX.

—— 1905. The chromosome complex of orthopteran spermatocytes. Biol. Bull. IX.

—— 1914. A comparative study of the chromosomes in orthopteran spermatogenesis. Jour. Morph. XXV.

—— 1917. The multiple chromosomes of Hesperotettix and Mermiria. *Ibid.* XXIX.

McPHEE, H. C. 1924. The influence of environment on sex in hemp, Cannabis sativa L. Jour. Agri. Research. XXVIII.

—— 1924. Meiotic cytokinesis of Cannabis. Bot. Gaz. LXXVIII.

MEHLING, E. 1915. Über die gynandromorphen Bienen des Eugsterschen Stockes. Verh. Phys.-Med. Gesell. Würzburg. XLIII.

MENDEL, G. 1865. Versuche über Pflanzen-hybriden. Verh. Naturf. Ver. Brünn. IV.

METZ, C. W. 1914. Chromosome studies in the Diptera. I. Jour. Exp. Zoöl. XVII.

—— 1916. Mutations in three species of Drosophila. Genetics. I.

—— 1916. Chromosome studies on the Diptera. II. The paired association of chromosomes in the Diptera, and its significance. Jour. Exp. Zoöl. XXI.

—— 1916. Chromosome studies on the Diptera. III. Additional types of chromosome groups in the Drosophilidae. Am. Nat. L.

—— 1916. Linked Mendelian characters in a new species of Drosophila. Science n.s. XLIV.

—— 1918. The linkage of eight sex-linked characters in Drosophila virilis. Genetics. III.

—— 1920. Correspondence between chromosome number and linkage groups in Drosophila virilis. Science n.s. LI.

—— 1920. The arrangement of genes in Drosophila virilis. Proc. Nat. Acad. Sc. VI.

—— 1925. Chromosomes and sex in Sciara. Science. LXI.

METZ, C. W., and BRIDGES, C. B. 1917. Incompatibility of mutant races in Drosophila. Proc. Nat. Acad. Sci. III.

METZ, C. W., and MOSES, M. S. 1923. Chromosomes of Drosophila. Jour. Heredity. XIV.

METZ, C. W.; MOSES, M.; and MASON, E. 1923. Genetic studies on Drosophila virilis, with considerations on the genetics of other species of Drosophila. Carnegie Inst. Wash. No. 328.

MEURMAN, O. 1925. Über Chromosomenzahlen und Heterochromosomen bei diözischen Phanerogamen. Soc. Sci. Fenn. Comm. Biol. II, 2.

—— 1925. The chromosome behavior of some dioecious plants and their relatives with special reference to the sex chromosomes. *Ibid.* II, 3.

MEVES, FR. 1907. Die Spermatocytenteilungen bei der Honigbiene Apis

mellifica (L.) nebst Bemerkungen über Chromatinreduktion. Arch. f. mikro. Anat. u. Entw.-mech. LXX.

MEYER, P. 1923. Crossing-over und Chromosomen. Ein Beitrag zur Frage des Faktorenaustauschmechanimus. Zeit. Abst.-Vererb. XXXII.

MINOURA, T. 1921. A study of testis and ovary grafts on the hen's egg and their effects on the embryo. Jour. Exp. Zoöl. XXXIII.

MOHR, O. L. 1919. Character changes caused by mutation of an entire region of a chromosome in Drosophila. Genetics. IV.

—— 1921. Den Morgan'ske skole og dens betydning for den moderne arvelighedsforskning. Nord. Jordbrugsforsk. Foren. Kongr. Kbenhavn.

—— 1922. Cases of mimic mutations and secondary mutations in the X-chromosome of Drosophila melanogaster. Zeit. Abst.-Vererb. XXVIII.

—— 1922. Ö. Winge's paper on "The interaction between two closely linked lethals in Drosophila as the cause of the apparent constancy of the mutant 'spread.'" Genetica. IV.

—— 1923. A somatic mutation in the singed locus of the X-chromosome in Drosophila melanogaster. Hereditas. IV.

—— 1923. Das Deficiency-Phänomen bei Drosophila melanogaster. Zeit. Abst.-Vererb. XXX.

—— 1923. A genetic and cytological analysis of a section deficiency involving four units of the X-chromosome in Drosophila melanogaster. *Ibid.* XXXII.

MOORE, C. R. 1919. On the physiological properties of the gonads as controllers of somatic and psychical characteristics. I. The rat. Jour. Exp. Zoöl. XXVIII.

—— 1925. Sex determination and sex differentiation in birds and mammals. Am. Nat. LIX.

DE MOL, W. E. 1921. De l'existence de variétés hétéroploïdes de l'Hyacinthus orientalis L. dans les cultures hollandaises. Inst. Bot. Universität Zürich Serie. II.

—— 1923. Duplication of generative nuclei by means of physiological stimuli and its significance. Genetica. V.

—— 1923. The disappearance of the diploid and triploid magnicoronate narcissi from the larger cultures and the appearance in their place of tetraploid forms. Proc. Koninklijke Akad. van Wetenschappen te Amsterdam. XXV.

MORGAN, L. V. 1922. Non-criss-cross inheritance in Drosophila melanogaster. Biol. Bull. XLII.

—— 1925. Polyploidy in Drosophila melanogaster with two attached X chromosomes. Genetics, X.

MORGAN, T. H. 1910. Sex-limited inheritance in Drosophila. Science n.s. XXXII.

—— 1910. The method of inheritance of two sex-limited characters in the same animal. Proc. Soc. Exp. Biol. and Med. VIII.

—— 1911. An attempt to analyze the constitution of the chromosomes on the basis of sex-limited inheritance in Drosophila. Jour. Exp. Zoöl. XI.

—— 1912. Further experiments with mutations in eye-color of Drosophila: the loss of the orange factor. Jour. Acad. Nat. Sci. Phila. XV.

—— 1912. Eight factors that show sex-linked inheritance in Drosophila. Science, n.s. XXXV.

—— 1912. Heredity of body color in Drosophila. Jour. Exp. Zoöl. XIII.
—— 1912. A modification of the sex-ratio, and of other ratios, in Drosophila through linkage. Zeits. Abst.-Vererb. VII.
—— 1912. The explanation of a new sex-ratio in Drosophila. Science n.s. XXXVI.
—— 1912. Complete linkage in the second chromosome of the male. *Ibid.* XXXVI.
—— 1912. The elimination of the sex-chromosomes from the male-producing eggs of Phylloxerans. Jour. Exp. Zoöl. XII.
—— 1914. The failure of ether to produce mutations in Drosophila. Amer. Nat. XLVIII.
—— 1914. No crossing over in the male of Drosophila of genes in the second and third pairs of chromosomes. Biol. Bull. XXVI.
—— 1914. Two sex-linked lethal factors in Drosophila and their influence on the sex-ratio. Jour. Exp. Zoöl. XVII.
—— 1914. Heredity and sex. New York.
—— 1915. The predetermination of sex in Phylloxerans and Aphids. Jour. Exp. Zoöl. XIX.
—— 1915. The infertility of rudimentary winged females of Drosophila Ampelophila. Amer. Nat. XLIX.
—— 1915. The constitution of the hereditary material. Proc. Amer. Phil. Soc. LIV.
—— 1915. The rôle of the environment in the realization of a sex-linked Mendelian character in Drosophila. Amer. Nat. XLIX.
—— 1915. Localization of the hereditary material in the germ cells. Proc. Nat. Acad. Sc. I.
—— 1916. A critique of the theory of evolution. Princeton Press.
—— 1917. An examination of the so-called process of contamination of the genes. Anat. Rec. XI.
—— 1917. The theory of the gene. Amer. Nat. LI.
—— 1918. Concerning the mutation theory. Sc. Mo. V.
—— 1918. Changes in factors through selection. *Ibid.* V.
—— 1918. Evolution by mutation. *Ibid.* VI.
—— 1919. A demonstration of genes modifying the character "notch." Carnegie Inst. Wash. No. 218.
—— 1919. The physical basis of heredity. Philadelphia.
—— 1922. The mechanism of heredity. Nature CIX, Feb. 23, Mar. 2, Mar. 9.
—— 1922. On the mechanism of heredity. Croonian Lecture. Proc. Roy. Soc., B. XCIV.
—— 1923. The modern theory of genetics and the problem of embryonic development. Physiol. Rev. III.
—— 1924. Are acquired characters inherited? Yale Review. XIII.
—— 1924. Human inheritance. Am. Nat. LVIII.
—— 1926. Recent results relating to chromosomes and genetics. Quart. Rev. Biol. I.
MORGAN, T. H., and BRIDGES, C. B. 1913. Dilution effects and bicolorism in certain eye colors of Drosophila. Jour. Exp. Zoöl. XV.
—— 1916. Sex-linked inheritance in Drosophila. Carnegie Inst. Wash. No. 237.

—— 1919. The construction of chromosome maps. Proc. Soc. Exp. Biol. and Med. XVI.

—— 1919. The origin of gynandromorphs. Carnegie Inst. Wash. No. 278.

—— 1919. The inheritance of a fluctuating character. Jour. Gen. Physiol. I.

MORGAN, T. H., BRIDGES, C. B., and STURTEVANT, A. H. 1925. The genetics of Drosophila. Bibliogr. Genetica, II.

MORGAN, T. H., and CATTELL, E. 1912. Data for the study of sex-linked inheritance in Drosophila. Jour. Exp. Zoöl. XIII.

—— 1913. Additional data for the study of sex-linked inheritance in Drosophila. *Ibid.* XIV.

MORGAN, T. H., and LYNCH, C. J. 1912. The linkage of two factors in Drosophila that are not sex-linked. Biol. Bull. XXIII.

MORGAN, T. H., and PLOUGH, H. H. 1915. The appearance of known mutations in other mutant stocks. Amer. Nat. XLIX.

MORGAN, T. H.; STURTEVANT, A. H.; and BRIDGES, C. B. 1920. The evidence for the linear order of the genes. Proc. Nat. Acad. Sc. VI.

MORGAN, T. H.; STURTEVANT, A. H.; MULLER, H. J.; and BRIDGES, C. B. 1915. 2d ed. 1923. The mechanism of Mendelian heredity. New York.

MORRILL, A. W. 1903. Notes on some Aleurodes from Massachusetts, with descriptions of new species. Mass. Agr. Exp. Sta., Tech. Bull. I.

MORRILL, A. W., and BACK, E. A. 1911. White flies injurious to citrus in Florida. U. S. Dept. Agr., Bureau Ent., Bull. 92.

MOUNCE, I. 1921. Homothallism and the production of fruit-bodies by monosporous mycelia in the genus Coprinus. Trans. Brit. Mycolog. Soc., VII.

MULLER, H. J. 1914. A gene for the fourth chromosome of Drosophila. Jour. Exp. Zoöl. XVII.

—— 1916. The mechanism of crossing over. Amer. Nat. L.

—— 1917. An Oenothera-like case in Drosophila. Proc. Nat. Acad. Sc. III.

—— 1918. Genetic variability, twin hybrids and constant hybrids, in a case of balanced lethal factors. Genetics. III.

—— 1920. Are the factors of heredity arranged in a line? Amer. Nat. LIV.

NACHTSHEIM, H. 1912. Parthenogenese, Eireifung und Geschlechtsbestimmung bei der Honigbiene. Sitzungs d. Gesell. f. Morph. u. Phys. in München.

—— 1913. Cytologische Studien über die Geschlechtsbestimmung bei der Honigbiene (Apis mellifica L.). Arch. Zellf. XI.

—— 1914. Das Problem der Geschlechtsbestimmung bei Dinophilus. Berich. d. Naturf. Gesell. z. Freiburg i. Br. XXI.

—— 1920. Crossing-over-Theorie oder Reduplikationshypothese? Zeit. Abst.-Vererb. XXII.

—— 1921. Sind haploide Organismen (Metazoen) lebensfähig? Biol. Zentralb. XLI.

NAWASCHIN, M. 1925. Morphologische Kernstudien der Crepis-Arten in bezug auf die Artbildung. Zeit. f. Zellf. u. mikr. Anat. II.

NAWASCHIN, S. 1912. On the dimorphism of the nuclei in the somatic cells of *Galtonia Candicana*. Bull. Acad. Imper. Sc. Pétersbourg, XXII. (Russian.)

—— 1915. Hetero- and idiochromosomes of the plant's nucleus as the cause

of the nuclear dimorphism of certain plant species, and the significance of nuclear dimorphism in the process of the origin of species. *Ibid.*

NĚMEC, B. 1910. Das Problem der Befruchtungsvorgänge und andere zytologische Fragen. Berlin.

NEWELL, W. 1915. Inheritance in the honey-bee. Science, XLI.

ORTMANN, A. E. 1905. Mem. Carnegie Mus. II.

OSAWA, I. 1913. Studies on the cytology of some species of Taraxacum. Arch. Zellf. X.

—— 1913. On the development of the pollen grain and embryo-sac of Daphne, with special reference to the sterility of Daphne odora. Jour. Coll. Agri. Tokyo. IV.

—— 1916. Triploid mutants in garden races of morus. Japanese. Bull. Imp. Sericult. Exp. Sta. Japan. I.

—— 1920. Cytological and experimental studies in morus, with special reference to triploid mutants. *Ibid.* I.

OSTENFELD, C. H. 1925. Some remarks on species and chromosomes. Am. Nat. LIX.

OVEREEM, C. VAN. 1921. Über Formen mit abweichender Chromosomenzahl bei Oenothera. Bot. Zentralb. XXXVIII.

—— 1922. Über Formen mit abweichender Chromosomenzahl bei Oenothera. *Ibid.* XXXIX.

PAINTER, T. S. 1922, 1923. Studies in mammalian spermatogenesis. I and II. Jour. Exp. Zoöl. XXXV and XXXVII.

PEACOCK, A. D. 1925. Animal parthenogenesis in relation to chromosomes and species. Am. Nat. LIX.

PEARL, R. 1917. The selection problem. Am. Nat. LI.

PEARL, R., and CURTIS, M. 1909. A case of incomplete hermaphroditism. Biol. Bull. XVII.

PEARL, R., and SURFACE, F. M. 1909. Is there a cumulative effect of selection? Data from the study of fecundity in the domestic fowl. Zeit. Abst.-Vererb. II.

PELLEW, C., and DURHAM, F. M. 1916. The genetic behavior of the hybrid Primula kewensis, and of its allies. Jour. Genet. V.

—— 1920. Weitere Untersuchungen über die Chromosomenverhältnisse in Crepis. Svensk Bot. Tidskr. XIV.

PERCIVAL, J. 1921. The wheat plant. London.

PFLÜGER, E. 1882. Über die geschlechtsbestimmenden Ursachen und die Geschlechtsverhältnisse der Frösche. Arch. f. Physiologie, XXIX.

—— 1883. Über den Einfluss der Schwerkraft auf die Theilung der Zellen. *Ibid.* XXXI. II. XXXII.

PHILIPPI, E. 1908. Fortpflanzungsgeschichte der viviparen Teleosteer Glaridichthys januarius, etc. Zool. Jahrb. XXVII.

PICK, L. 1914. Über den wahren Hermaphroditismus des Menschen und der Säugetiere. Arch. f. mikr. Anat. LXXXIV.

PICTET, A., et FERRERO, A. 1924. Ségrégation dans un croisement entre espèces de Cobayes (Cavia aperea par Cavia cobaya). Soc. d. phys. et d'his. nat. d. Genève. XLI.

PLOUGH, H. H. 1917. The effect of temperature on linkage in the second chromosome of Drosophila. Proc. Nat. Acad. Sc. III.

—— 1917. The effect of temperature on crossingover in Drosophila. Jour. Exp. Zoöl. XXIV.

—— 1919. Linear arrangement of genes and double crossing over. Proc. Nat. Acad. Sc. V.

—— 1921. Further studies on the effect of temperature on crossing over. Jour. Exp. Zoöl. XXXII.

—— 1924. Radium radiations and crossing over. Amer. Nat. LVIII.

PONSE, K. 1924. L'organe de Bidder et le déterminisme des caractères sexuels secondaires du Crapaud (Bufo vulgaris L.). Rev. Suisse d. Zool. XXXI.

—— 1925. Ponte et dévelopment d'oeufs provenant de l'organe de Bidder d'un Crapaud mâle féminisé. C. R. Soc. Biol. XCII.

PONSE, K., et GUYÉNOT, E. 1923. Inversion expérimentale du type sexuel dans la gonade du Crapaud. C. R. Soc. Biol. LXXXIX.

PRITCHARD, F. S. 1916. Change of sex in hemp. Jour. Heredity. VII.

PUNNETT, R. C. 1913. Reduplication in Sweet Peas. Jour. Genet. III.

—— 1917. Reduplication in Sweet Peas. II. *Ibid.* VI.

—— 1923. Linkage in the Sweet Pea (Lathyrus odoratus). *Ibid.* XIII.

—— 1924. Lathyrus odoratus. Bibliogr. Genetica, I.

—— 1927. Linkage groups and chromosome numbers in Lathyrus. Proc. Roy. Soc. London (B), C II.

RENNER, O. 1917. Versuche über die gametische Konstitution der Oenotheren. Zeit. Abst.-Vererb. XVIII.

—— 1918. Oenothera Lamarckiana und die Mutationstheorie. Die Naturwissenschaften. VI.

RIDDLE, O. 1916. Sex control and known correlations in pigeons. Am. Nat. L.

—— 1917. The control of the sex ratio. Jour. Wash. Acad. Sc. VII.

—— 1917. The theory of sex as stated in terms of results of studies on pigeons. Science, n.s. XLVI.

—— 1924. A case of complete sex-reversal in the adult pigeon. Am. Nat. LVIII.

—— 1925. Birds without gonads: Their origin, behaviour, and bearing on the theory of the internal secretion of the testis. Brit. Jour. Exp. Biol. II.

ROSENBERG, O. 1909. Über die Chromosomenzahlen bei Taraxacum und Rosa. Svensk. Bot. Tidskr. III.

—— 1917. Die Reduktionsteilung und ihre Degeneration in Hieracium. *Ibid.* XI.

—— 1925. Chromosomes and species. Am. Nat. LIX.

—— 1927. Die semiheterotypische Teilung und ihre Bedeutung für die Entstehung verdoppelter Chromosomenzahlen. Hereditas, VIII.

SAFIR, S. R. 1920. Genetic and cytological examination of the phenomena of primary non-disjunction in Drosophila melanogaster. *Ibid.* V.

SAKAMURA, T. 1916. Über die Beeinflussung der Zell- und Kernteilung durch die Chloralisierung mit besonderer Rücksicht auf das Verhalten der Chromosomen. Bot. Mag. Tokyo. XXX.

—— 1918. Kurze Mitteilung über die Chromosomenzahlen und die Verwandtschaftsverhältnisse der Triticum-Arten. *Ibid.* XXXII.

—— 1920. Experimentelle Studien über die Zell- und Kernteilung mit beson-

derer Rücksicht auf Form, grösse und Zahl der Chromosomen. Jour. Coll. Sci. Imp. Univ. Tokyo. XXXIX.

SANTOS, J. K. 1923. Differentiation among chromosomes in Elodea. Bot. Gaz. LXXV.

—— 1924. Determination of sex in Elodea. *Ibid.* LXXVII.

SAX, K. 1921. Sterility in wheat hybrids. I. Sterility relationships and endosperm development. Genetics, VI.

—— 1922. Sterility in wheat hybrids. II. Chromosome behavior in partially sterile hybrids. *Ibid.* VII.

SCHACKE, M. A. 1919. A chromosome difference between the sexes of Sphaerocarpus texanus. Science, n.s. XLIX.

SCHAFFNER, J. H. 1919. Complete reversal of sex in hemp. Science. L.

—— 1921. Influence of environment on sexual expression in hemp. Bot. Gaz. LXXI.

—— 1923. The influence of relative length of daylight on the reversal of sex in hemp. Ecology. IV.

—— 1925. Sex determination and sex differentiation in the higher plants. Am. Nat. LIX.

SCHLEIP, W. 1911. Das Verhalten des Chromatins bei Angiostomum (Rhabdonema) nigrovenosum. Arch. Zellf. VII.

SCHMIDT, JOHS. 1920. The genetic behaviour of a secondary sexual character. IV. Compt.-rend. des Travaux d. Laboratoire Carlsberg. XIV.

SCHRADER, F. 1920. Sex determination in the white-fly (Trialeurodes vaporariorum). Jour. Morph. XXXIV.

—— 1923. Haploidie bei einer Spinnmilbe. Arch. mikr. Anat. XCVII.

—— 1926. Notes on the English and American races of the green-house white-fly (Trialeurodes vaporariorum). Ann. Appl. Biol. XIII.

—— 1928. Die Geschlechtschromosomen. Berlin.

SCHRADER, F., and HUGHES-SCHRADER, S. 1926. Haploidy in Icerya purchasi. Zeit. wiss. Zool. CXXVIII.

SCHREINER, A., and K. E. 1905. Über die Entwickelung der männlichen Geschlechtszellen von Myxine glutinosa (L.). Arch. de Biol. XXI.

SCHWEIZER, JAKOB. 1923. Polyploidie und Geschlechterverteilung bei Splachnum sphaericum (Linn. Fil.) Swartz. Flora. CXVI.

SEILER, J. 1913. Das Verhalten der Geschlechtschromosomen bei Lepidopteren. Zool. Anz. XLI.

—— 1917. Geschlechtschromosomen-Untersuchungen an Psychiden. Zeit. Abst.-Vererb. XVIII.

—— 1917. Zytologische Vererbungsstudien an Schmetterlingen. Sitzungs. Ges. naturf. Fr. Berlin. II.

—— 1919. Researches on the sex-chromosomes of Psychidae (Lepidoptera). Biol. Bull. XXXVI.

—— 1920. Geschlechtschromosomen-Untersuchungen an Psychiden. I. Experimentelle Beeinflussung der geschlechtsbestimmenden Reifeteilung bei Talaeporia tubulosa Retz. Arch. Zellf. XV.

—— 1921. Geschlechtschromosomen-Untersuchungen an Psychiden. II. Die Chromosomenzahlen von Fumea casta und Talaeporia tubulosa. *Ibid.* XVI.

—— 1922. Geschlechtschromosomen-Untersuchungen an Psychiden. III. Chromosomenkoppelungen bei Solenobia pineti Z. *Ibid.* XVI.

—— 1923. Geschlechtschromosomen-Untersuchungen an Psychiden. IV. Die Parthenogenese der Psychiden. Zeit. Abst.-Vererb. XXXI.
SEILER, J., und HANIEL, C. B. 1922. Das verschiedene Verhalten der Chromosomen in Eireifung und Samenreifung von Lymantria monacha L. Zeit. Abst.-Vererb. XXVII.
SEREBROVSKY, A. S. 1922. Crossing-over involving three sex-linked genes in chickens. Am. Nat. LVI.
SEXTON, E. W., and HUXLEY, J. S. 1921. Intersexes in Gammarus cheureuxi and related forms. Jour. Marine Biol. Assn. United Kingdom. XII.
SHARP, L. W. 1921. An introduction to cytology. New York.
SHIMOTOMAI, N. 1925. A karyological study of Brassica I. Bot. Mag. Tokyo, XXXIX.
SHIWAGO, P. J. 1924. The chromosome complexes in the somatic cells of male and female of the domestic chicken. Science. LX.
SHULL, A. F. 1910. Studies in the life cycle of Hydatina senta. Jour. Exp. Zoöl. VIII.
—— 1915. Inheritance in Hydatina senta. II. Characters of the females and their parthenogenetic eggs. Jour. Exp. Zoöl. XVIII.
—— 1915. Periodicity in the production of males in Hydatina senta. Biol. Bull. XXVIII.
—— 1917. Sex determination in Anthothrips verbasci. Genetics, II.
—— 1921. Chromosomes and the life cycle of Hydatina senta. Biol. Bull. XLI.
—— 1925. Sex and the parthenogenetic-bisexual cycle. Am. Nat. LIX.
SHULL, A. F., and LADOFF, SONIA. 1916. Factors affecting male-production in Hydatina. Jour. Exp. Zoöl. XXI.
SHULL, G. H. 1909. The "presence and absence" hypothesis. Am. Nat. XLIII.
—— 1910. Inheritance of sex in Lychnis. Bot. Gaz. XLIX.
—— 1911. Reversible sex-mutants in Lychnis dioica. *Ibid.* LII.
—— 1912. Hermaphrodite females in Lychnis dioica. Science. XXXVI.
—— 1914. Duplicate genes for capsule-form in Bursa bursa-pastoris. Zeit. Abst.-Vererb. XII.
—— 1923. Further evidence of linkage with crossing over in Oenothera. Genetics. VIII.
—— 1923. Linkage with lethal factors in the solution of the Oenothera problem. Eugenics, Genetics and the Family. I.
SINNOTT, E. W., and BLAKESLEE, A. F. 1922. Structural changes associated with factor mutations and with chromosome mutations in Datura. Proc. Nat. Acad. Sc. VIII.
SINOTO, Y. 1924. On the chromosome behaviour and sex determination in Rumex acetosa L. Bot. Mag. Tokyo, XXXVIII.
SMITH, GEOFFREY. 1906. Fauna und Flora des Golfes von Neapel. Rhizocephala. Zool. Sta. Neapel. Monographie. XXIX.
—— 1909. Crustacea. Cam. Nat. Hist.
—— 1910-1912. Studies in the experimental analysis of sex. Parts 1-9. Quar. Jour. Micro. Sc. LIV, LV, LVI, LVII, LVIII.
—— 1913. Studies in the experimental analysis of sex. 10. The effect of Sacculina on the storage of fat and glycogen and on the formation of pigment by its host. *Ibid.* LIX.

SOROKINE, HELEN. 1924. The satellites in the somatic mitoses in Ranunculus acris L. Publ. de la fac. des sciences de l'univ. Prague Nr. 13.

SPEMANN, H. 1914. Über verzögerte Kernversorgung von Keimteilen. Verh. d. Dtsch. Zool. Ges. a. d. 24. Jahrevers., Freiburg i. Br.

SPENCER, H. 1864. The principles of biology.

STEINACH, E. 1913. Feminierung von Männchen und Maskulierung von Weibchen. Centralb. f. Phys. XXVII.

—— 1916. Pubertätsdrüsen und Zwitterbildung. Arch. f. d. Entw. d. Organ. XLII.

STEINER, G. 1923. Intersexes in Nematodes. Jour. Heredity. XIV.

STEVENS, N. M. 1905. Studies in spermatogenesis with especial reference to the accessory chromosome. Carnegie Inst. Wash. No. 36.

—— 1909. An unpaired chromosome in the aphids. Jour. Exp. Zoöl. VI.

—— 1911. Heterochromosomes in the guinea-pig. Biol. Bull. XXI.

STOCKARD, C. R. 1913. The effect on the offspring of intoxicating the male parent and the transmission of the defects to subsequent generations. Am. Nat. XLVII.

—— 1916. The hereditary transmission of degeneracy and deformities by the descendants of alcoholized mammals. Interstate Med. Jour. XXIII.

—— 1923. Experimental modification of the germplasm and its bearing on the inheritance of acquired characters. Am. Phil. Soc. LXII.

STOCKARD, C. R., and PAPANICOLAOU, G. 1916. A further analysis of the hereditary transmission of degeneracy and deformities by the descendants of alcoholized mammals. II. Am. Nat. L.

—— 1918. Further studies on the modification of the germ-cells in mammals: The effect of alcohol on treated guinea-pigs and their descendants. Jour. Exp. Zoöl. XXVI.

STOLL, N. R., and SHULL, A. F. 1919. Sex determination in the white fly. Genetics, IV.

STOMPS, T. J. 1912. Die Entstehung von Oenothera gigas. Ber. Deutsch. Bot. Ges. XXX.

—— 1916. Über den Zusammenhang zwischen Statur und Chromosomenzahl bei den Oenotheren. Biol. Centralbl. XXXVI.

STOUT, A. B. 1919. Intersexes in Plantago lanceolata. Bot. Gaz. LXVIII.

STRASBURGER, E. 1910. Über geschlechtbestimmende Ursachen. Jahr. f. wiss Bot. XLVIII.

STRONG, R. M. 1912. Results of hybridizing ring-doves, including sex-linked inheritance. Biol. Bull. XXIII.

STURTEVANT, A. H. 1913. A third group of linked genes in Drosophila ampelophila. Science, n.s. XXXVII.

—— 1913. The linear arrangement of six sex-linked factors in Drosophila, as shown by their mode of association. Jour. Exp. Zoöl. XIV.

—— 1914. The reduplication hypothesis as applied to Drosophila. Amer. Nat. XLVIII.

—— 1915. The behavior of the chromosomes as studied through linkage. Zeit. Abst.-Vererb. XIII.

—— 1915. Experiments on sex recognition and the problem of sexual selection in Drosophila. Jour. An. Behav. V.

—— 1915. A sex-linked character in Drosophila repleta. Amer. Nat. XLIX.

—— 1916. Notes on North American Drosophilidae with descriptions of twenty-three new species. Ann. Ent. Soc. Amer. IX.
—— 1917. Crossing over without chiasmatype? Genetics. II.
—— 1917. An analysis of the effect of selection on bristle number in a mutant race of Drosophila. Anat. Rec. XI.
—— 1917. Genetic factors affecting the strength of linkage in Drosophila. Proc. Nat. Acad. Sc. III.
—— 1918. An analysis of the effects of selection. Carnegie Inst. Wash. No. 264.
—— 1918. A synopsis of the Neartic species of the genus Drosophila (Sensu lato). Bull. Amer. Mus. Nat. Hist. XXXVIII.
—— 1918. A parallel mutation in Drosophila funebris. Science, XLVIII.
—— 1919. Inherited linkage variations in the second chromosome. Carnegie Inst. Wash. No. 278.
—— 1920. Intersexes in Drosophila simulans. Science, n.s. LI.
—— 1920. The vermilion gene and gynandromorphism. Proc. Soc. Exp. Biol. and Med. XVII.
—— 1920. Genetic studies on Drosophila simulans. I. Introduction. Hybrids with D. melanogaster. Genetics. V.
—— 1921. Genetic studies on Drosophila simulans. II. Sex-linked group of genes. *Ibid.* VI. III. Autosomal genes. General discussion. *Ibid.* VI.
—— 1921. The North American species of Drosophila. Carnegie Inst. Wash. No. 301.
—— 1921. Linkage variation and chromosome maps. Proc. Nat. Acad. Sc. VII.
—— 1921. A case of rearrangement of genes in Drosophila. *Ibid.* VII.
—— 1925. The effect of unequal crossing-over at the bar locus in Drosophila. Genetics. X.
STURTEVANT, A. H.; BRIDGES, C. B.; and MORGAN, T. H. 1919. The spatial relations of genes. Proc. Nat. Acad. Sc. V.
STURTEVANT, A. H., and MORGAN, T. H. 1923. Reverse mutation of the bar gene correlated with crossing over. Science, n.s. LVII.
STURTEVANT, A. H., and SCHRADER, F. 1923. A note on the theory of sex determination. Amer. Nat. LXII.
SWINGLE, W. 1920. Neoteny and the sexual problem. Am. Nat. LIV.
—— 1922. Is there a transformation of sex in frogs? *Ibid.* LVI.
—— 1925. Sex differentiation in the bullfrog (Rana catesbeiana). *Ibid.* LIX.
TÄCKHOLM, G. 1920. On the cytology of the genus Rosa. Svensk. Bot. Tidskr. XIV.
—— 1922. Zytologische Studien über die Gattung Rosa. Acta Horti Bergiani. VII.
TAHARA, M. 1921. Cytologische Studien an einigen Kompositen. Jour. Coll. Sc. Tokyo Imp. Univ. XLIII.
TANAKA, Y. 1913. A study of Mendelian factors in the silkworm Bombyx mori. Jour. Coll. Agr. Tohoku Imp. Univ. (Sapporo, Japan). V.
—— 1913. Gametic coupling and repulsion in silkworms. *Ibid.* V.
—— 1914. Sexual dimorphism of gametic series in the reduplication. Trans. Sapporo Nat. Hist. Soc. V.

—— 1914. Further data on the reduplication in silkworms. Jour. Coll. Agr. Tohoku Imp. Univ. (Sapporo, Japan). VI.

—— 1915. Occurrence of different systems of gametic reduplication in male and female hybrids. Zeit. Abst.-Vererb. XIV.

—— 1916. Genetic studies on the silkworm. Jour. Coll. Agr. Tohoku Imp. Univ. VII.

—— 1922. Sex-linkage in the silkworm. Jour. Genet. XII.

—— 1924. Maternal inheritance in Bombyx mori. Genetics. IX.

TANDLER, J., und GROSZ, S. 1913. Die biologischen Grundlagen der sekundären Geschlechtscharaktere. Berlin.

TANDLER, J., and KELLER, K. 1910. Über den Einfluss der Kastration auf den Organismus. IV. Die Körperform der weiblichen Frühkastraten des Rindes. Arch. Entw.-Mech. XXXI.

—— 1911. Über das Verhalten des Chorions bei verschiedengeschlechtlicher Zwillingsgravidität des Rindes und über die Morphologie den Genitalien der weiblichen Tiere, welche einer solchen Gravidität entstammen. Deutsche tierärztliche Wochenschrift. No. 10.

TAUSON, A. 1924. Die Reifungsprozesse der parthenogenetischen Eier von Asplanchna intermedia Huds. Zeit. Zellf. mikr. Anat. I.

—— 1927. Die Spermatogenese bei Asplanchna intermedia Huds. *Ibid.* IV.

TAYLOR, W. R. 1920. A morphological and cytological study of reproduction in the genus Acer. Bot. Contrib. Univ. Pa. V.

TENNENT, D. H. 1911. A heterochromosome of male origin in Echinoids. Biol. Bull. XXI.

—— 1912. Studies in cytology, I and II. Jour. Exp. Zoöl. XII.

THOMSEN, M. 1925. Sex determination in Trialeurodes vaporariorum. Nature, CXVI, p. 428.

TISCHLER, G. 1916. Chromosomenzahl, -Form und -Individualität im Pflanzenreiche. Progressus rei bot. V.

TOURNOIS, J. 1911. Anomalies florales du houblon Japonais et du chanvre déterminées par des semis Hâtip. Compt. rend. l'Acad. Sc. Paris. CLIII.

TOYAMA, K. 1906. On the hybridology of the silkworms. Rep. Sericultural Assn. Japan.

—— 1906. Studies on the hybridology of insects. I. On some silkworm crosses, with special reference to Mendel's law of heredity. Bull. Coll. Agr. Tokyo Imp. Univ. VII.

—— 1912. On certain characteristics of the silk-worm which are apparently non-Mendelian. Biol. Centralb. XXXII.

TROW, A. H. 1913. Forms of reduplication—primary and secondary. Jour. Genet. II.

—— 1916. A criticism of the hypothesis of linkage and crossing over. *Ibid.* V.

TSCHERMAK, E., und BLEIER, H. 1926. Über fruchtbare Aegilops-Weizenbastarde. Ber. Deutsch. Bot. Ges. XLIV.

TURNER, C. L. 1924. Studies on the secondary sexual characters of crayfishes. I. Male secondary sexual characters in females of Cambarus propinquus. Biol. Bull. XLVI.

VANDENDRIES, R. 1923. Recherches sur le déterminisme sexuel des Basidiomycètes. Bruxelles.

—— 1923. Nouvelles recherches sur la sexualité des Basidiomycètes. Bull. Soc. Royale d. Bot. d. Belgique, XVI.

DE LA VAULX. 1919. L'intersexualité chez un crustacé cladocère Daphne atkinsoni. Baird. Compt. rend. Acad. d. Sc. CLXIX.

DE VRIES, H. 1901-1903. Die Mutationstheorie. Leipzig.

—— 1905. Species and varieties; their origin by mutation. Chicago.

—— 1907. Plant-breeding; comments on the experiments of Nilsson and Burbank. Chicago.

—— 1907. On twin hybrids. Bot. Gaz. XLIV.

—— 1908. Bastarde von Oenothera gigas. Ber. Deutsch. Bot. Gesell. XXVIa.

—— 1908. Über die Zwillingsbastarde von Oenothera nanella. *Ibid.* XXVI.

—— 1909. On triple hybrids. Bot. Gaz. XLVII.

—— 1910. Intracellular Pangenesis. Trans.

—— 1911. Über doppeltreziproke Bastarde von Oenothera biennis und O. muricata. Biol. Centralb. XXXI.

—— 1913. Gruppenweise Artbildung. Berlin.

—— 1914. The probable origin of Oenothera Lamarckiana Ser. Bot. Gaz. LVII.

—— 1915. Oenothera gigas nanella, a Mendelian mutant. *Ibid.* LX.

—— 1916. New dimorphic mutants of the Oenotheras. *Ibid.* LXII.

—— 1924. On physiological chromomeres. La Cellule. XXXV.

DE VRIES, H., and BOEDIJN, K. 1923. On the distribution of mutant characters among the chromosomes of Oenothera Lamarckiana. Genetics. VIII.

—— 1924. Double chromosomes of Oenothera Lamarckiana semigigas. Bot. Gaz. LXXVIII.

WALTON, A. C. 1924. Studies on nematode gametogenesis. Zeit. f. Zell. u. Geweb. I.

WEINSTEIN, A. 1918. Coincidence of crossing over in Drosophila melanogaster (ampelophila). Genetics. III.

—— 1920. Homologous genes and linear linkage in Drosophila virilis. Proc. Nat. Acad. Sc. VI.

—— 1922. Crossing over, non-disjunction, and mutation in Drosophila virilis. Sigma Xi Quar. X.

WEISMANN, A. 1883. Über Vererbung. Jena.

—— 1902. The germ plasm. Trans.

WENRICH, D. H. 1916. The spermatogenesis of Phrynotettix magnus with special reference to synapsis and the individuality of the chromosomes. Bull. Mus. Comp. Zoöl. Harv. Coll. LX.

WETTSTEIN, F. v. 1923. Kreuzungsversuche mit multiploiden Moosrassen. I. Biol. Zentralb. XLIII. 1924. II. *Ibid.* XLIV.

—— 1924. Gattungskreuzungen bei Moosen. Zeit. Abst.-Vererb. XXXIII.

—— 1924. Morphologie und Physiologie des Formwechsels der Moose auf genetischer Grundlage. I. *Ibid.* XXXIII.

WHITE, O. E. 1916. Inheritance studies in Pisum. I. Inheritance of cotyledon color. Am. Nat. L.

—— 1917. Studies of inheritance in Pisum. II. The present state of knowledge of heredity and variation in peas. Proc. Am. Phil. Soc. LVI.

—— 1918. Inheritance studies in Pisum. III. The inheritance of height in peas. Mem. Torrey Bot. Club. XVII.

—— 1917. Inheritance studies in Pisum. IV. Interrelation of the genetic factors of Pisum. Jour. Agri. Research. XI.

WHITING, ANNA R. 1925. The inheritance of sterility and of other defects induced by abnormal fertilization in the parasitic wasp, Hadrobracon juglandis (Ashmead). Genetics. X.

WHITING, P. W. 1918. Sex-determination and biology of a parasitic wasp, Hadrobracon brevicornis (Wesmael). Biol. Bull. XXXIV.

—— 1919. Genetic studies on the Mediterranean flour-moth, Ephestia Kühniella Zeller. Jour. Exp. Zoöl. XXVIII.

—— 1921. Studies on the parasitic wasp, Hadrobracon brevicornis (Wesmael). I. Genetics of an orange-eyed mutation and the production of mosaic males from fertilized eggs. Biol. Bull. XLI. II. A lethal factor linked with orange. *Ibid.* XLI.

—— 1921. Rearing meal moths and parasitic wasps for experimental purposes. Jour. Heredity. XII.

—— 1921. Heredity in wasps. The study of heredity in a parthenogenetic insect, the parasitic wasp, Hadrobracon. *Ibid.* XII.

—— 1924. A study of hereditary and environmental factors determining a variable character. Defective and freak venation in the parasitic wasp, Hadrobracon juglandis (Ash.). Studies in child welfare. Univ. Iowa. First Series. No. 73. III.

WHITNEY, D. D. 1909. Observations on the maturation stages of parthenogenetic and sexual eggs of Hydatina senta. Jour. Exp. Zoöl. VI.

—— 1914. The influence of food in controlling sex in Hydatina senta. *Ibid.* XVII.

—— 1916. The control of sex by food in five species of rotifers. *Ibid.* XX.

—— 1917. The relative influence of food and oxygen in controlling sex in rotifers. *Ibid.* XXIV.

—— 1917. The production of functional and rudimentary spermatozoa in rotifers. Biol. Bull. XXXIII.

—— 1918. Further studies on the production of functional and rudimentary spermatozoa in rotifers. *Ibid.* XXXIV.

—— 1924. The chromosome cycle in the rotifer Asplanchna intermedia. Anat. Rec. XXIX.

WIEMAN, H. L. 1917. The chromosomes of human spermatocytes. Am. Jour. Anat. XXI.

WILLIAMS, C. B. 1917. Some problems of sex ratios and parthenogenesis. Jour. Genet. VI.

WILLIER, B. H. 1921. Structures and homologies of free-martin gonads. Jour. Exp. Zoöl. XXXIII.

WILSON, E. B. 1899 (revised 1928). The cell in development and inheritance. New York.

—— 1905-1910. Studies on chromosomes, I to VI. Jour. Exp. Zoöl. II, III, VI, IX.

—— 1910. The chromosomes in relation to the determination of sex. Sc. Progress. No. 16.

—— 1911. Studies on chromosomes. VII. Jour. Morph. XXII.

—— 1911. The sex chromosomes. Arch. f. Mikr. Anat. LXXVII.

—— 1912. Studies on chromosomes. VIII. Jour. Exp. Zoöl. XIII.

—— 1914. *Croonian Lecture:* The bearing of cytological research on heredity. Proc. Roy. Soc., B. LXXXVIII.

WILSON, E. B., and MORGAN, T. H. 1920. Chiasmatype and crossing over. Am. Nat. LIV.

WINGE, Ö. 1914. The pollination and fertilization processes in Humulus lupulus L. and H. Japonicus Seib. et Zucc. C. R. Trav. Labor. Carlsberg. XI.

—— 1917. The chromosomes. Their numbers and general importance. *Ibid.* XIII.

—— 1920. Verbreitung und Ursache der Parthenogenesis im Pflanzen- und Tierreiche. Jena.

—— 1921. On a partial sex-linked inheritance of eye-colour in man. C. R. Trav. Labor. Carlsberg. XIV.

—— 1922. A peculiar mode of inheritance and its cytological explanation. Jour. Genetics. XII. One-sided masculine and sex-linked inheritance in Lebistes reticulatus. *Ibid.* XII.

—— 1923. Crossing-over between the X- and the Y-chromosome in Lebistes. Jour. Genet. XIII.

—— 1923. On sex chromosomes, sex determination, and preponderance of females in some dioecious plants. Compt. rend. d. trav. d. Lab. d. Carlsberg. XV.

—— 1924. Zytologische untersuchungen über Speltoide und andere mutantenähnliche aberranten beim Weizen. Hereditas. V.

—— 1927. The location of eighteen genes in Lebistes reticulatus. Jour. Genet. XVIII.

WINIWARTER, H. DE. 1921. La formule chromosomiale dans l'espèce humaine. Compt. rend. séances d. la Société d. Biol. LXXXV.

—— 1921. Chiasmatypie et reduction. *Ibid.* LXXXV.

WINKLER, H. 1907. Über Pfropfbastarde und pflanzliche Chimären. Ber. Deutsch. Bot. Ges. XXV.

—— 1908. Solanum tubingense, eim echter Pfropfbastard zwischen Tomate und Nachtschatten. *Ibid.* XXVIa.

—— 1910. Über die Nachkommenschaft der Solanum Pfropfbastarde und die Chromosomenzahlen ihrer Keimzellen. Zeit. f. Bot. II. Rev. in Zeit. Abst.-Vererb. III.

—— 1913-1914. Die Chimärenforschung als Methode der experimentellen Biologie. Verh. Phys.-Med. Gesell. Würzburg. XLII.

—— 1916. Über die experimentelle Erzeugung von Pflanzen mit abweichenden Chromosomenzahlen. Zeit. f. Bot. VIII.

WITSCHI, E. 1921. Der Hermaphroditismus der Frösche und seine Bedeutung für das Geschlechtsproblem und die Lehre von der inneren Sekretion der Keimdrüsen. Arch. Entw.-Mech. XLIX.

—— 1921. Development of gonads and transformation of sex in the frog. Am. Nat. LV.

—— 1922. Experimente mit Froschzwittern. Verhandl. Deutsch. Gesell. f. Vererb. Wien.

—— 1922. Vererbung und Zytologie des Geschlechts nach Untersuchungen an Fröschen. Zeit. Abst.-Vererb. XXIX.

—— 1923. Über die genetische Konstitution der Froschzwitter. Biol. Zentralb. XLIII.

—— 1923. Über bestimmt gerichtete Variation von Erbfaktoren. Studia Mendeliana. Brünn.

—— 1923. Ergebnisse der neuren Arbeiten über die Geschlechtsprobleme bei Amphibien. Zeit. Abst.-Vereb. XXXI.

—— 1923. Über geographische Variation und Artbildung. Rev. Suisse d. Zool. XXX.

—— 1924. Die Entwicklung der Keimzellen der Rana temporaria L. I. Urkeimzellen und Spermatogenese. Zeit. f. Zelle. und Geweb. I.

—— 1924. Die Beweise für die Umwandlung weiblicher Jungfrösche in männliche nach uteriner Überreife der Eier. Arch. f. Mikro. Anat. u. Entw.-mech. CII.

—— 1928. Effect of high temperature on the gonads of frog larvae. Proc. Soc. Exp. Biol. and Medicine. XXV.

WODSEDALEK, J. E. 1913, 1914, 1920. (a) Spermatogenesis in the pig, etc. (b) Spermatogenesis of the horse, etc. (c) Studies on the cells of cattle with special reference to the accessory chromosome and chromotoid body. Biol. Bull. XXV, XXVI, XXXVIII.

WOLTERECK, R. 1911. Über Veränderung der Sexualität bei Daphniden. Leipzig.

YAMPOLSKY, C. 1919. Inheritance of sex in Mercurialis annua. Am. Jour. Bot. VI.

YATSU, N. 1921. On the changes in the reproductive organs in heterosexual parabiosis of albino rats. Anat. Rec. XXI.

ZAWADOWSKY, M. 1923. Die Entwicklungsmechanik des Geschlechts. (Russian, with German summary.) Moscow.

ZELENY, C. 1917. Full-eye and emarginate-eye from bar-eye in Drosophila without change in the bar gene. Abst. 15th Ann. Meet., Am. Soc. Zoöl.

—— 1917. Selection for high-facet and for low-facet number in the bar-eyed race of Drosophila. *Ibid.*

—— 1920. A change in the bar gene of Drosophila melanogaster involving further decrease in facet number and increase in dominance. Jour. Exp. Zoöl. XXX.

ZELENY, C., and MATTOON, E. W. 1915. The effect of selection upon the "bar-eye" mutant of Drosophila. *Ibid.* XIX.

DE ZULUETA, A. 1925. La herencia ligada al sexo en el coleóptero Phytodecta variabilis (Ol.) "Eos" I.

INDEX

A

abnormal abdomen, 302.
Abraxas, 61, 62, 208, 209, 256.
absence of genes, 74-77, 85.
Acer, 170.
Agar, 264.
Aida, 222, 223, 226.
albinos, 65.
allelomorphs, multiple, 92, 93.
Allen, 128, 215, 239.
amphibia, 205.
Andalusian fowl, 292.
Angiostomum, 231, 232.
Anthothrips, 149.
Antirrhinum, 97, 98.
Aphelopus, 263.
aphids, 228, 229, 230.
Aplocheilus, 223.
Archieracium, 167.
Artemia, 108, 109.
Artom, 108, 109.
Ascaris, 38, 39, 107, 108, **136, 219**, 220.
atavism, 85.
Atriplex, 171.
attached-X, 56-58.
Avery, 177.
avian type, 206.

B

Babcock, 194.
Bagg, 308, 309, 310.
Baker, 260.
balanced genes, 124.
Baltzer, 139, 265.
Banta, 264.
bar-eye, 86-91.
bar-infra-bar, **90, 91.**
barley, 150.
barnacles, 264.
Basidiomycetes, 242.
Bateson, 10, 17, 318.
Baur, 97, 98.
bee, 106, 144-146, 214, 235-237.
Bělař, 213.
Bellamy, 266.
Belling, 119-122, 132-134, 177, 180, 182, 185, 186.
Benoit, 283-285.
Bensaude, 242.
bent wings, 86.
Bidder's organ, 277-279.
birds, 282-286.
Blackburn, 158, 214.
Blakeslee, 118-124, 133, 134, **142**, 143, 177-186.
Boedijn, 110, 188.
Bonellia, 264, 265.
Boveri, 38, 108, 142, 145, 220, 231.
brachydactyly in man, 64.
Brecher, 304.
Bremer, 170.
Bridges, 79, 80, 135, 136, 175, 241, 252, 253, 256.
Bufo, 277.
Buller, 242.
bullfrog, 269-276.
Burns, 286.
butterflies, 206, 304.

C

Callitriche, 171.
Campanula, 171.

Canina roses, 159, 163, 164.
Canna, 133.
Cannabis, 287.
Cape bees, 237.
Carex, 170, 171.
Carothers, 35, 36.
Castle, 69, 296-300.
cattle, 260.
Cavia, 99.
Champy, 280.
Chapin, 259.
chart of chromosomes, 22, 23.
chiasmatype, 41.
chimaera, 113.
chromosome continuity, 37-39.
chromosomes and genes, 45-58.
chromosomes of Oenothera gigas, 109.
chromosomes of O. Lamarckiana, 109.
chromosomes of sweet pea, 36.
chrysanthemums, 168, 169.
Clausen, 143, 192, 193.
Cleland, 110, 111.
Cocklebur, 181, 182.
Collins, 194.
combs of fowls, 72, 73.
Coprinus, 243-245, 248.
corn, 82, 83, 85, 124, 196, 296.
corn, flinty, 83, 84.
corn, floury, 83, 84.
Correns, 96, 214, 287, 289.
coupling, 17.
crayfish, 264.
Crepidula, 265.
Crepis, 194, 195.
Crew, 260, 275, 276, 282.
crossing-over, 14-22, 24.
Cuénot, 296.
Cunningham, 265.
curly, 63.

D

daphnians, 264.
Darwin, 67, 298-300, 315.
Darwin's pangenesis, 28.
Datura, 118, 119, 121, 122, 1
134, 142, 143, 177, 179, 1
183.
Davis, 69, 110, 111.
Delage, 28.
Della Valle, 107.
Detlefsen, 98.
Dinophilus, 231.
Domm, 285.
Doncaster, 256.
double-bar, 87.
double-infra-bar, 87.
double-X, 56-58.
Drosera, 171, 191.
Drosophila melanogaster, 11-
40, 41, 47, 48, 50-52, 59,
64-66, 70, 75, 84-93, 99-1
104, 135, 136, 175, 201-2
241, 252-254, 293, 302, 3
315.
D. obscura, 103, 104.
D. simulans, 100, 101.
D. virilis, 102, 104.
Dürken, 304-306.

E

East, 96, 246, 249, 296.
Ectocarpus, 246, 248.
Einkorn, 151-153, 156, 157.
Elodea, 212, 213.
Emerson, S. H., 190.
Emmer wheat, 163-168.
endosperm, 82-84.
enzymes, 257.
Essenberg, 266.
Euchlaena, 123, 187.
eyeless, 48, 49, 51, 52, 75, 303.

F

Farnham, 133, 177.
Federley, 136, 137, 198, 211.
ferns, 214.
fish, 205.
flowering plants, 212.
four-o'clock, 5-7, 301, 302.
fowls, 72, 73, 206, 208.
free martin, 258.
frog's eggs, 139.
Fumea, 209, 210.

G

Galton, 66.
gametophyte, 125, 126.
Gammarus, 264.
Gates, 131, 172, 173.
Geerts, 131.
Geinitz, 219.
Gelei, 43.
gemmules, 29.
genes, 45-58.
germ-plasm, 28, 29.
Giard, 262, 263.
gipsy moth, 254, 255.
Glarydichthys, 266.
Goldschmidt, 222, 254-257.
Goodale, 282, 283, 285.
Goodspeed, 192, 193.
Gould, 265.
grasshoppers, 35, 36.
Gregory, 112.
guinea pig, 74, 98, 99, 205, 293, 307.
Guyénot, 278.

H

Habrobracon, 237-239.
Hance, 314.
Hanna, 242.
haplo-IV, 47-49, 81, 176, 177.
haploids, 139-149.
Hargreaves, 148.
Harman, 260.
Harms, 266, 278-280.
Harris, 281.
Harrison, 158.
Hartmann, 246-248.
hawthorns, 171.
Hayes, 296.
Heilborn, 170.
Helix, 99.
hemp, 287-290.
hermaphrodites, 260, 264, 265, 27
Hertwig, G., 140.
Hertwig, O., 140, 273.
Hertwig, R., 269, 272, 273.
Hertzenstein, 266.
Hesperotettix, 221.
heteroploids, 172-190.
Hieracium, 165-167.
Hindle, 149.
honey bee, 144.
hooded rats, 296-298.
horse, 205.
Hovasse, 107.
Humulus, 212, 213.
Hurst, 158, 163, 164.
Huxley, 264.
hyacinth, 132, 133.
Hydatina, 147.
Hymenoptera, 206, 241.

I

ids, 29, 30.
Indian corn, 37.
infra-bar, 87, 89, 90, 91.
infra-bar-bar, 90, 91.
insect type, 199.
intersex, 136, 252, 253, 254-257.

J

Janssens, 41, 42.
Jimson weed, 118, 177.
Johannsen, 294-296.
jungle fowl, 75.
Junker, 266-268.

K

Keller, 258.
Kihara, 151, 152, 154-157, 212.
Kniep, 242.
Kornhauser, 263.
Kuschakewitsch, 272.
Kuttner, 264.
Kuwada, 187.

L

Lactuca, 171.
Lamarck, 300, 301.
Lamarck's theory, 30.
Lancefield, 103, 104.
Lang, 99.
lata types, 70.
Lebistes, 222, 226, 228.
leghorn fowl, 75.
Lepidoptera, 206.
Lillie, 258, 259.
linear order, 22.
linkage, 10-12, 14-20, 24.
linkage groups, 22, 23, 36, 48.
Little, 308.
liverworts, 128, 149, 214-216.
Ljundahl, 197, 198.
lobe, 62, 63.
Longley, 123, 124, 171, 196.
loss of gene, 94.
Lutz, Anne, 131, 173.
Lygaeus, 200.
Lymantria, 255.

M

m-chromosome, 105.
McClung, 221.
MacDowell, 296.
McPhee, 287, 289.
Magnussen, 258, 259.
maize, 124.
man, 203, 204, 205.
man, eye color, 4, 5.
Mangelsdorf, 249.
Mann, 143, 194.
map of the chromosomes, 22, 23.
maples, 170.
Marchal, Él. and Ém., 125, 126, 128, 214, 216, 218, 239.
maturation of germ-cells, 33, 34.
May, 86.
mechanism of crossing-over, 39-44.
Mehling, 145.
Melandrium, 213, 214.
Mendel, 72.
Mendel's laws, 1-25, 59.
Mercurialis, 290, 291.
Metapodius, 105, 106.
Metz, 92, 102, 104.
Meves, 146.
Miastor, 281.
mice, 296.
Mirabilis, 6.
mites, 149.
Mohr, 79.
de Mol, 124, 132, 133.
Morgan, L. V., 82.
Morgan, T. H., 88.
Morrill, 148.
Morus, 169.
mosses, 124-128, 149, 214.
moths, 206.
Mounce, 242.
mulberry, 169.

Muller, 112.
mutant characters, 59-71.
mutation theory, 67, 68, 95.
Myxine, 265.

N

Nachtsheim, 145, 231.
Nansen, 265.
Narcissus, 124.
Nematodes, 206, 231.
Newell, 237.
Nicotiana, 96, 143, 144, 192, 193, 249.
nightshade, 112-116.
non-disjunction, 53-55.
notch wing, 77-81.

O

oats, 150.
Oenothera, 105, 131, 132.
O. franciscana, 111.
O. gigas, 70, 109, 110.
O. Lamarckiana, 69, 71, 109, 110, 172, 187, 188.
O. lata, 172-174, 189.
O. semilata, 172, 189.
Oguma, 205.
Oligarces, 281.
Ono, 212.
opossum, 205.
Osawa, 169.
Overeem, van, 131.

P

Painter, 203, 204.
pangenesis, 28.
Papaver, 171, 197, 198.
parabiotic twins, 286.
particulate theory of heredity, 26-31.
pea comb, 72, 73, 74.
pea, edible, 2, 7-10, 36, 37.
pea, sweet, 10, 11.
Peltogaster, 263.
Percival, 151.
Perla, 266-268.
Pflüger, 267, 272.
Philippi, 266.
Phragmatobia, 105, 211.
Phylloxerans, 228-230.
physiological units, 28.
Pick, 260.
Pieris, 304.
pigs, 260.
Planaria, 44.
planarian crossing-over, 43
Plantago, 171.
Platanthera, 171.
Poinsettia, 177, 181, 182.
pollen grains, 10.
polyploid roses, 158-165.
Polyploids, 150-171.
Ponse, 278-280.
poppy, 197, 198.
poultry, 207.
Prange, 260.
Primula sinensis, 112.
Pritchard, 287, 288.
Protenor, 200.
protonema, 126.
Punnett, 10, 17, 36.
Pygaera, 136, 137, 198, 211

R

rabbit, albino, 74.
rabbit, black, 75.
rabbits, 296, 301.
radium, 139.
Rana, 269-276.
raspberries, 171.
rats, 74, 296-298, 309.
recessive characters, 74.

recurrent mutations, 66.
repulsion, 17.
retrograde variety, 69.
reverse mutations, 85.
Riddle, 283.
ring dove, 283.
Rosa, 163.
rose comb, 72, 73, 74.
Rosenberg, 165, 166, 167, 191
roses, 158-165.
rotifer, 147, 214, 233, 234, 241.
round worms, 206.
Rumex, 212, 213.
rye, 150, 158.

S

Saccharum, 170.
Sacculina, 263.
Sakamura, 152.
salamander, 286.
Santos, 212.
Sax, 152, 155, 156.
Schaffner, 287.
Schleip, 231, 232.
Schmidt, 128, 222, 226.
Schrader, 148.
scute, bristles, 86.
sea urchins, 206.
Seiler, 105, 209, 210, 220, 256, 314.
semi-gigas, 70.
semi-lata types, 70.
sesquiplex mutant type, 189.
sex, 199-218, 219.
sex-chromosomes, 32, 52-55, 199-218.
sex-determination, 219.
sex-linkage, 52.
sex-linked inheritance, 207, 208.
sex reversals, 261-291.
Sexton, 264.
sheep, 260.
Shiwago, 206, 208.
Shull, A. F., 149.
Shull, G. H., 71, 189, 190.
single comb, 73, 74.
Sinnott, 180.
Smith, G., 262-264.
snail, 99.
snapdragon, 97.
Solenobia, 210.
Solanum, 112-114.
species, 68.
"Species and Varieties," 68.
Spemann, 139, 140.
Spencer, Herbert, 28.
Sphaerocarpus, 239.
spider crab, 262.
sporophyte, 125, 126.
stable type, 124.
Stevens, 208.
Stockard, 207, 208.
Stomps, 70.
stone fly, 266.
Sturtevant, 88-91, 101, 102, 254.
sugar cane, 170.
superfemale, 56, 253.
supermale, 136, 252.
sweet peas, 10, 11, 36, 37.
Swingle, 269.

T

Täckholm, 158-163.
tadpole, 267-276.
Tahara, 167-169.
Talaeporia, 210.
Tandler, 258.
Tauson, 233.
Taylor, 170.
teosinte, 123, 124, 187, 196.
tetraploids, 105-130.
tetra-type, 176.

Thelia, 263.
theories of heredity, 26-31.
theory of the gene, 25.
thrips, 149.
Tischler, 170.
toad, 277.
tobacco, 96, 249.
tomato, 112, 113, 115-117.
translocation, 80-82.
Trialeurodes, 148.
triplo-IV, 50, 51, 175, 176.
triploid Drosophila, 84.
triploid endosperm, 82.
triploids, 131-138.
trisomic type, 177-189.
Triticum, 151, 152.
Triton, 140, 280.
twins, 258, 286.

V

Vallisneria, 213, 214.
vermilion genes, 81, 82.
vestigial, 75.
Viola, 171.
de Vries, 67, 68, 69, 70, 71, 95, 109, 131, 174, 187, 188, 189.
Vulgare wheat, 152, 154-157.

W

walnut comb, 72, 73, 74.
wasp, 237.
W-chromosome, 256, 257.
Wedge, 182.
Weinstein, 102, 104.
Weismann, 28-30.
Wettstein, 128, 149, 216, 217, 218, 239, 242.
wheats, polyploids, 150-158.
White, O. E., 37.
Whiting, Anna R., 239.
Whiting, 237-239.
Whitney, 147, 233, 234.
Williams, 148.
Willier, 259.
Winge, 214, 222, 223, 226, 227, 228.
Winiwarter, 203-205.
Winkler, 112-118.
Wiry, 181, 182.
Witschi, 269-276, 280.
Wright, 298.

X

Xiphophorus, 265, 266.

Y

Yampolsky, 290.
Y-chromosome, 52, 105, 222, 239.
yellow mice, 64.

Z

Zea mays, 123.
Zeleny, 86.